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METALLURGICAL MATERIALS
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METALLURGICAL MATERIALS and PROCESSES

by

JOHN ELBERFELD
Dean of Engineering
Worcester Junior College

New York
PRENTICE-HALL, INC.
1948

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FOREWORD

It is difficult to think of an industry that does not use metals in some way, either as raw materials or in the form of machinery. This book is designed to provide persons working or intending to work in industry with a general background in the science of metals. It is written in such a manner that it may be used either for home study or in the classroom.

The subject matter and the manner in which it is presented were chosen to make the book useful as a text in metallurgy for students specializing in other fields. It is suitable for use in colleges, junior colleges, technical institutes, apprentice training programs, and evening school courses.

A considerable amount of space is devoted to grain structure and constitution diagrams since the author feels that a knowledge of these topics is necessary for an understanding of the effects of operations and alloying upon the properties of metals. Such topics as heat-treating furnaces and their controls, the forming of metals, welding metallurgy, powder metallurgy, and laboratory procedure are included. It is expected that both the student and the instructor will make free use of standard reference books such as *Machinery's Handbook* and the ASM *Metals Handbook*.

To make the book more suitable for classroom use, questions and a summary accompany each chapter. Such instructional aids as lists of laboratory equipment and an outline of a suggested laboratory course are included in the Appendix. Also, an outline of the necessary chemistry for an understanding of the text material can be found in the Appendix. The author has found that about two class hours spent in studying the chemistry outlined in the Appendix precludes the necessity of a chemistry prerequisite.

If a student wishes to look more deeply into a particular subject, he may consult the bibliography. This bibliography is divided by topics to make it easier to find the desired material. The numerous pictures in the text were chosen to illustrate the most modern methods and equipment.

The author wishes to thank the many companies who have been so co-operative in furnishing illustrations and information. Credit is given to each of these companies in the text. (Figures 1-2, 1-3, and 1-5 are reproduced by permission from John Elberfeld, *Strength and Properties of Materials*, New York, Harper & Brothers, 1942.)

Special acknowledgment is given to the author's wife, who deciphered an almost illegible handwriting and typed the manuscript.

JOHN ELBERFELD

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REFERENCE READING LIST 173

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Chapter 1

THE REFINING OF METALS

METALS AS they come from the earth are usually mixed with other materials or are chemically combined with other materials to form compounds. To be of commercial use, the metal must be separated from all unwanted materials. The metal in its natural state is called an *ore*, and the earthy material which comes with the ore is called the *gangue*. To change an ore to a useful product, the following procedure is usually required:

(1) Extraction of the desired metal from other ore materials.
(2) Refinement of the metal to eliminate impurities.
(3) Addition of alloying elements.

Iron. Iron is separated from its ore by the use of a blast furnace (Fig. 1-1). The process is called *smelting*. A *blast furnace* is a round, brick-lined, steel shell ranging up to 100 feet high and 27 feet in hearth diameter. The usual output is about 700 tons of pig iron per day, although some furnaces can produce as much as 1200 tons daily. The *charge*, which consists of coke, flux (limestone), and ore, is carried to the top of the furnace in *skip-cars* and dumped into the furnace through two *hoppers*. Two hoppers and their *bells* are used to prevent gases from escaping into the air.

The coke has two functions: to supply the heat for melting the ore and to supply carbon for reducing[1] the ore. The main purposes of the limestone are to lower the melting temperatures of the earthy materials and to remove some of the sulphur.

The ores of iron consist of oxides and sulphides of iron, but the greater part of iron is produced from the oxides of iron, Fe_2O_3 and Fe_3O_4. Fe_2O_3 is ordinary rust or red iron. The percentage of iron in these oxides can be figured by using their atomic weights. The atomic weight of iron is 55.84 and that of oxygen is 16; therefore, the percentage of iron in Fe_2O_3 is given by

$$\frac{2 \times 55.84}{2 \times 55.84 + 3 \times 16} \times 100 = 70\%$$

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[1] Chemical terms are explained in Appendix A.

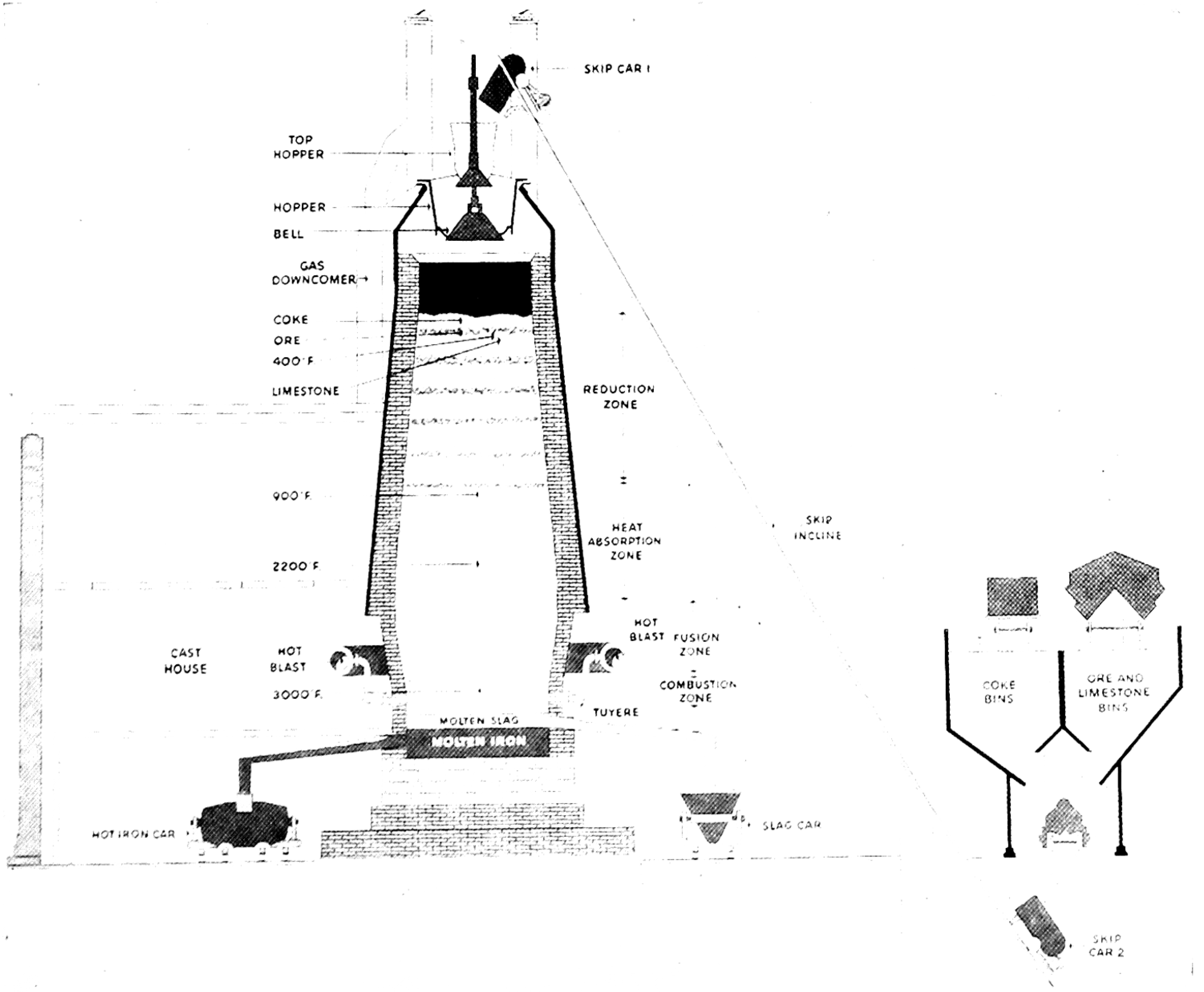


Fig. 1-1. Cross section showing general construction of a blast furnace in which pig iron is made. *Courtesy Bethlehem Steel Company.*

The percentage of iron in Fe_3O_4 is about 72%. Actually, these percentages are reduced by the gangue to from 50% to 55%. Iron is obtained from the oxide by reduction; coke is used as the reducing agent.

Adjacent to the blast furnace are three or four *stoves* whose function is to preheat the air to be used in the furnace. These stoves are cylinders about 100 feet in height and 22 feet in diameter, which are filled with a checker-work of fire bricks. This arrangement permits an easy passage for the hot blast-furnace exhaust gases and also presents a large heating surface. When operating, the hot exhaust gases are washed, and then they are passed through all but one of the stoves to heat the bricks. When a stove is sufficiently hot, air is forced through it, thus preheating it to about 1400 F before it is delivered to the blast furnace through the *tuyères*.

In the operation of the blast furnace, the charge is put in through the hoppers in alternate layers of flux, coke, and ore. The approximate proportions of the material entering the furnace are 1000 lb of coke, 2000 lb of ore, 500 lb of flux, and 4000 lb of preheated air. In proportion to the above input, the output would be about 1000 lb of iron, 500 lb of slag, and 6000 lb of waste gases. *Slag* is the waste product taken off in a liquid state. At the top of the furnace, where the temperature is about 600 F, the Fe_2O_3 is reduced by the hot CO to FeO and CO_2. As the FeO drops down the furnace to a temperature zone of 1300 F to 1500 F, the FeO is reduced to Fe by carbon. A spongy mass of iron results, which drops to a temperature zone of 1500 F to 2500 F, where it absorbs heat and all the carbon it can hold, that is, a maximum amount of about 3.5% to 4%. The absorbed carbon lowers the melting temperature of the iron so that it melts and runs to the bottom of the furnace, where its temperature reaches 2500 F. The slag also melts at about 2500 F and then floats on the molten iron.

The slag is drawn off at frequent intervals and hauled away to the slag banks in large pots mounted on railway trucks. At one time, slag was a waste product, but now it is used in the manufacture of cement and in place of crushed stone in road building. It is also made into mineral-wool insulation material by blowing a jet of high-pressure steam into a stream of molten slag.

The iron is tapped from the furnace four or five times every 24 hours and is cast into small bars called pigs, hence the name *pig iron*. In large plants, the iron is drawn off into special hot-metal cars and hauled to large refractory-lined tanks known as *hot-metal mixers*, where it is stored at a uniform temperature until it is used in the steel-making furnaces. The high carbon content of pig iron makes it weak and brittle but gives

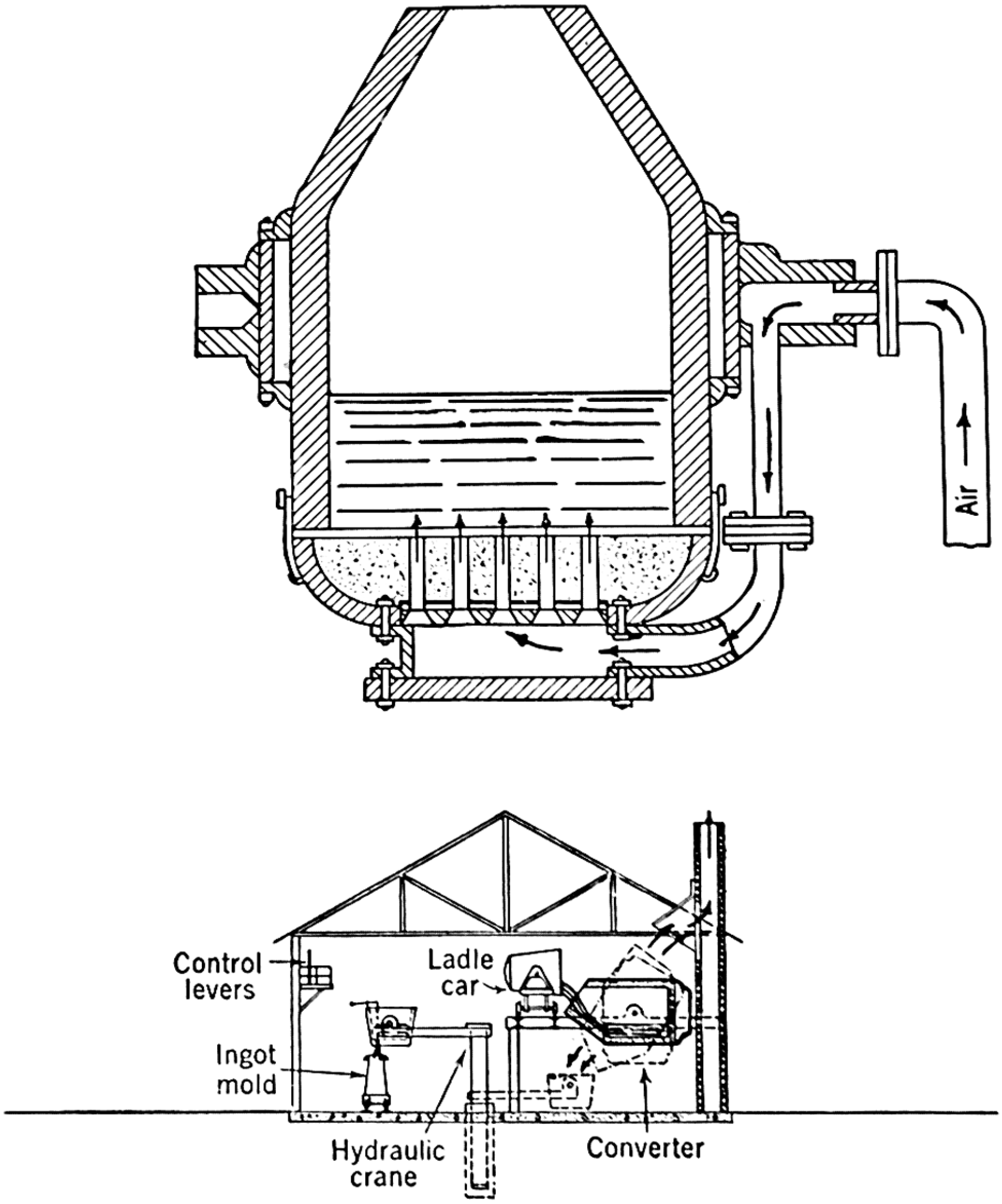


Fig. 1–2. Bessemer converter.

it good fluidity at a low temperature, making pig iron good for casting purposes.

Steel. The properties and the name of iron change with the percentage of carbon content. Up to 0.2% carbon content, the iron may be called low-carbon steel or wrought iron, depending upon the manufacturing method; between 0.1% and 1.5% carbon, it is called steel; and in the vicinity of 3.5% carbon, it is known as cast iron.

Since pig iron contains about 4% carbon, it is clear that carbon must be removed in order to obtain steel. The undesirable elements must be oxidized and then removed as a gas or as molten slag. Only a small percentage of iron is lost by oxidation when modern equipment is used.

Bessemer process. The Bessemer Converter (Fig. 1-2) is a refractory-lined, pear-shaped steel shell. It is 10 feet or more in height, open at the top and mounted on trunnions so that it may be tilted for loading or pouring.

After 15 to 25 tons of molten pig iron have been loaded into the converter, air is forced up through the metal. Each ton of pig iron contains about 75 pounds of carbon, 25 pounds of silicon, one pound of sulphur, and 15 pounds of manganese. These impurities are oxidized by the oxygen of the air. A large amount of heat energy is thus liberated, and the temperature of the metal rises from about 2200 F to 3500 F.

After about 20 minutes, the bright flames of the burning impurities die down and the *blow* is finished. The correct amounts of carbon and manganese are then added to get the desired type of steel, which is cast into uniform shapes about 2 feet square and 6 feet high called *ingots*. The ingots can then be formed into the desired shapes by rolling, forging, or other processes.

Bessemer steel is used for the cheaper grades of sheet steel, wire, butt-welled pipes, and free-machining screw stock. In spite of the high rate of production possible with the Bessemer process, only about 11% of the steel made in the United States is made in this way: the process is so fast that control is poor.

Open-hearth process. In the open-hearth process, from 5 to 250 tons of steel are contained in a saucer-like vessel over which preheated gases are burned. The fuel is a gas rich in unburned carbon; it is made in special, separate stoves. In Fig. 1-3, air and unburned gas enter on the right, through separate networks of preheated bricks, to mix and burn over the charge. The charge for a basic furnace consists of pig iron, possibly scrap steel, iron oxide, and lime. The limestone is charged first in order to build up a protective slag, then the scrap steel is charged.

After the scrap steel has melted, pig iron, usually molten, is added.

When solid pig iron is used, it is added as soon as the scrap steel has melted sufficiently to provide space. If alloy steels are wanted, the alloying material is added after some of the refining has taken place.

In the open-hearth furnace, little excess oxygen is left from the air after the gas has been burned. Therefore, some other means of oxidizing the carbon must be used. The iron oxide is mixed with the charge to provide the necessary oxygen to oxidize the carbon, silicon, manganese, and phosphorous. Since most fuels contain sulphur, and are therefore constantly replacing whatever sulphur may have been oxidized, this impurity is very hard to remove.

The hot gases are exhausted through the brick networks on the left, thereby heating the bricks. When these bricks are hot, a matter of 15 to 20 minutes, the gas flow is reversed to provide continuously hot bricks for preheating purposes.

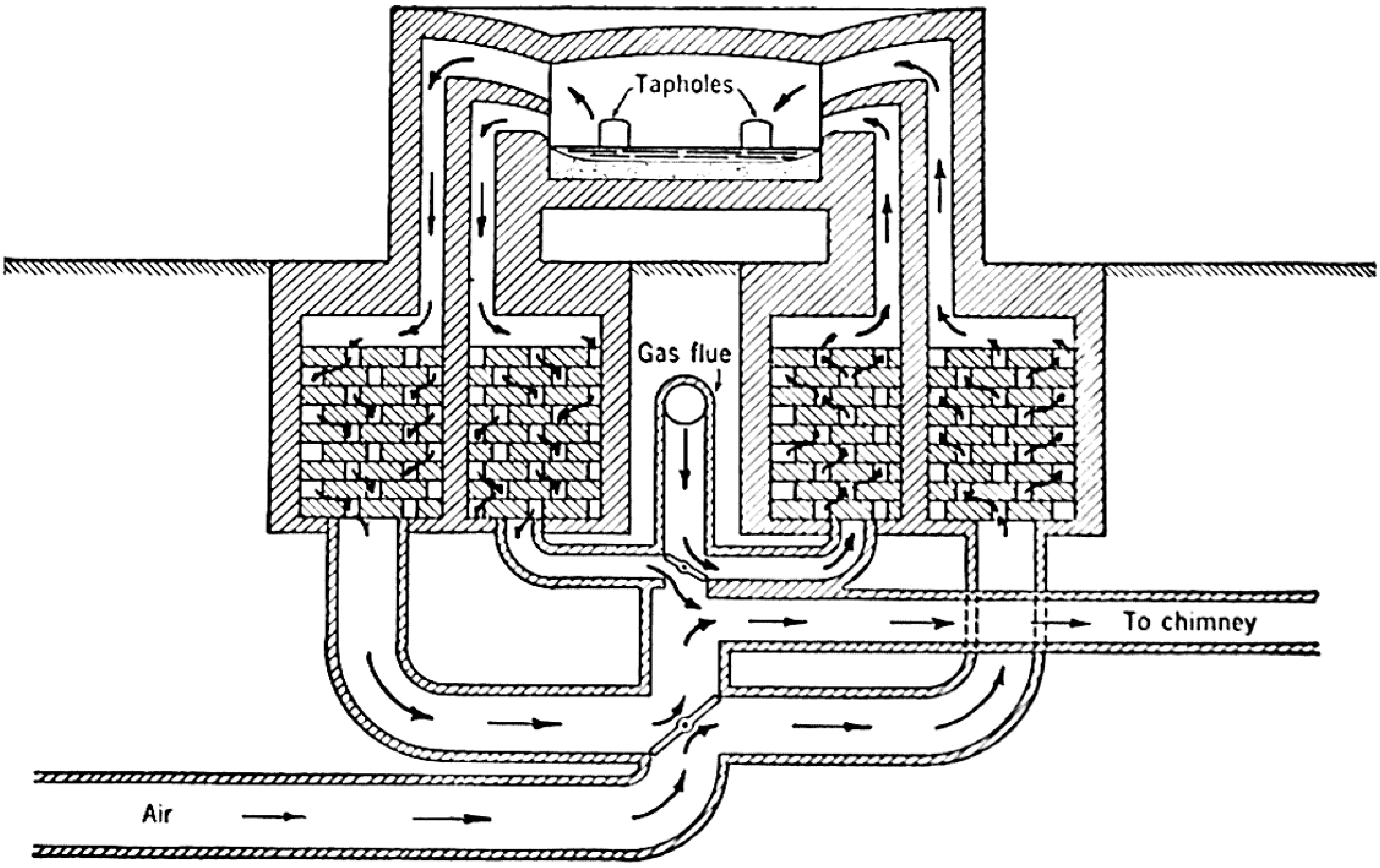


Fig. 1-3. Open-hearth furnace for making steel.

The open-hearth process, lasting 8 to 12 hours, is much slower than the Bessemer process, but the product is more refined. This is because there is time to analyze samples frequently, thus providing a close control, and also because scientific instruments may be used to closely control the temperatures, the furnace atmosphere, and other conditions. The product of the open-hearth furnace (80% to 90% of steel made in the United States) is used for steel castings, structural shapes, rods, plates, and spring steels.

Electric furnaces. Electric furnaces are able to produce highly refined steel, since they can create high temperatures without the introduction of air and fuel gas, with their undesirable constituents. The most common types of electric furnaces are the electric-arc and the induction types.

The *electric-arc furnace* (Fig. 1-4) is a steel shell lined with either silica brick (acid) or magnesite (basic), depending upon the impurities in the steel to be refined. The furnace is charged through the door on the side, and is tilted to pour the refined steel from a spout. Heat is obtained by passing a heavy electric current through the metal between the three carbon electrodes. These electrodes can be raised or lowered in order to regulate the amount of current and consequently the temperature. The capacities of these furnaces range from 1 to 100 tons. The charge may be either cold metal, or molten metal which needs further refining. Since the furnace may be tilted to pour off the top part of the charge, one kind of floating slag can be poured off and then another built up. Thus, more types of impurities can be removed.

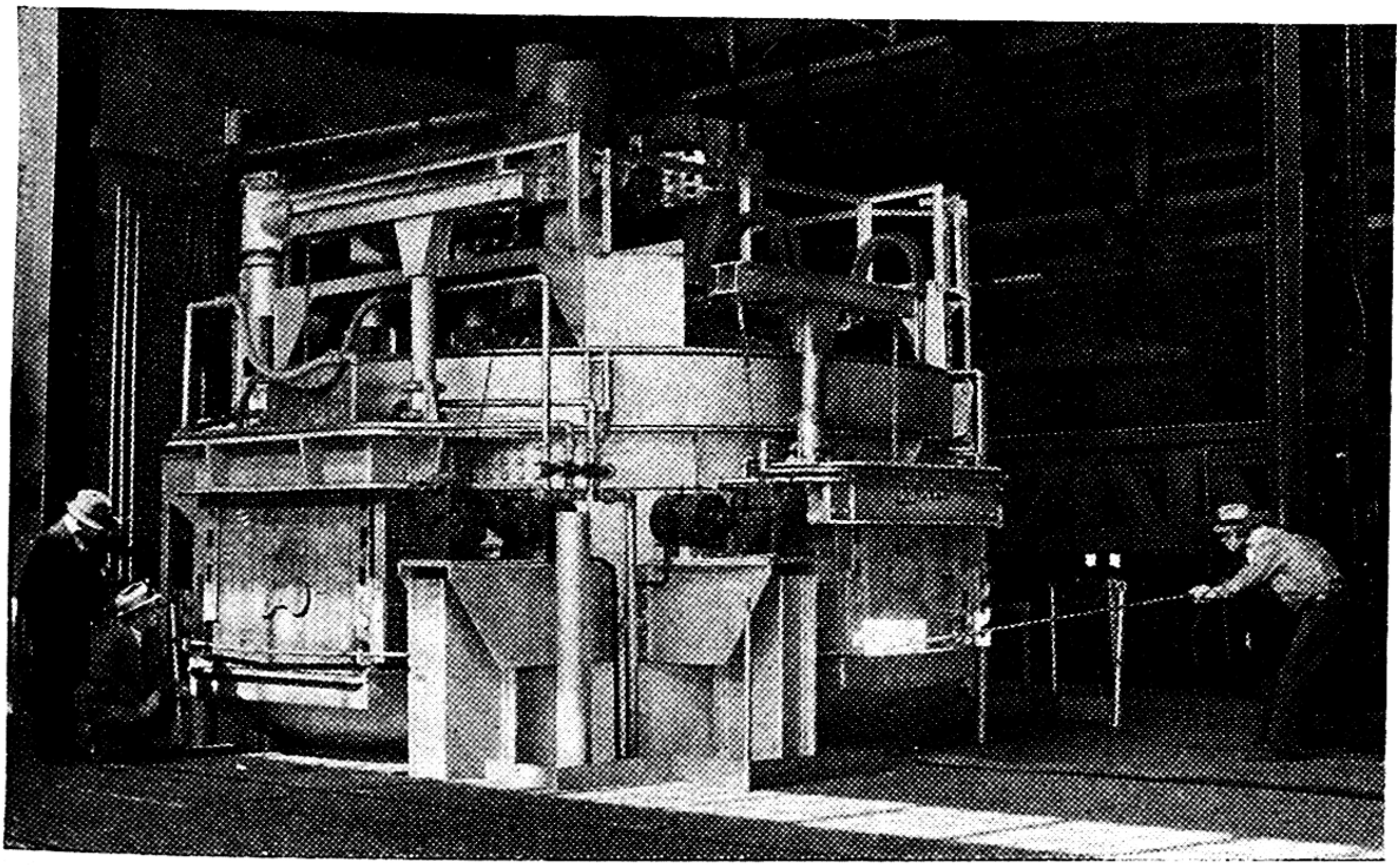


Fig. 1-4. A 50-ton electric-arc furnace. High-grade tool and alloy steels are made in this type of furnace. *Courtesy Bethlehem Steel Company.*

The *induction furnace* is essentially a crucible set inside a coil of wire. High-frequency electric currents flow through the coil and induce eddy currents in the metallic charge. The electrical resistance to these currents causes heat to be produced deep within the metal. The coils are usually copper tubing which is kept cool by a continuous flow of water through the tubing. The product is a closely controlled, high-grade steel, and capacities range from one pound to five or more tons.

Cast iron. Cast iron, which is made from pig iron and scrap iron, is refined in a *cupola furnace*, where the impurities are removed and the correct ingredients are added. The iron, coke, flux (limestone), and alloying elements are charged into the cupola furnace (Fig. 1-5) in alternate layers until the level reaches the charging door. As the charge melts, the level goes down and more material may be charged. Thus the furnace can be kept in operation until the lining needs repairs. The coke is the fuel which provides the heat for melting the iron; the flux lowers the melting point of the impurities. As molten slag and iron collect at the bottom of the furnace, they are drawn off, and the iron is carried in ladles to the casting molds.

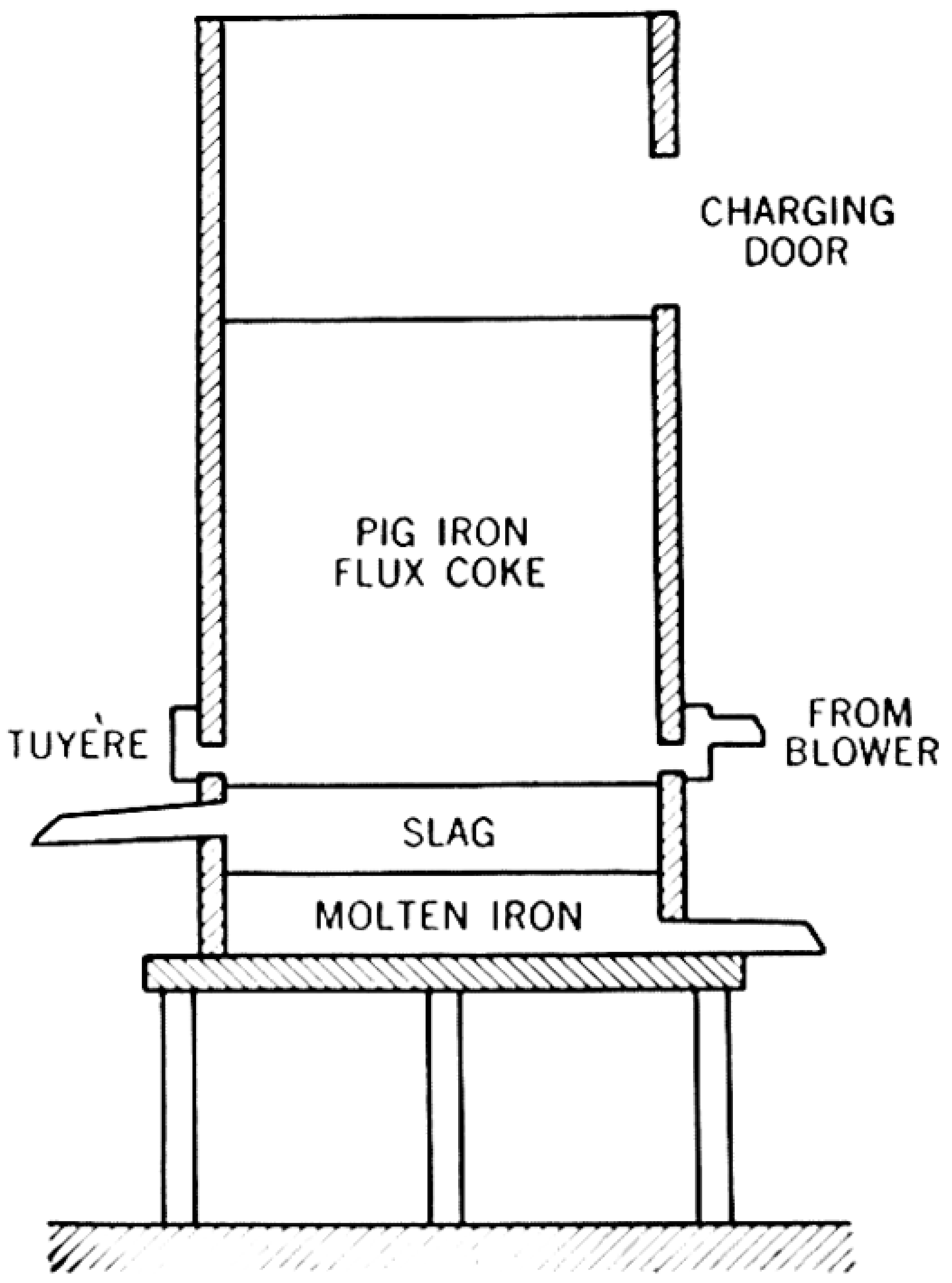


Fig. 1-5. Cupola furnace for making cast iron.

Malleable cast iron. Cast iron as it comes from the cupola is hard and brittle, and for many uses, such as for large hammers and railroad bumpers, it is desirable to have a more shock-resistant material. If white cast iron is packed in iron oxide and allowed to stand for about three days at temperatures of from 600 F to 1600 F, some of the carbon will be drawn out of the casting as CO_2, leaving a more shock-resistant material. The carbon that remains is in the form of free graphite, which helps to make the casting less brittle.

Wrought iron. This type of iron is comparatively pure except for small amounts of slag, which give it a fibrous appearance. A *reverberatory furnace* is charged with molten iron directly from the blast furnace and then a flux is added. A reverberatory furnace heats the charge largely by reflection and radiation from the roof, as in the open-hearth furnace. The molten iron, which rests on a layer of iron oxide, is stirred to produce a thorough mixing of the metal and the oxide. Oxygen from the iron oxide oxidizes the carbon and the sulphur to form gases which escape; the silicon and the phosphorous unite with the flux to form slag.

In the *puddling process* the iron is collected on the ends of steel rods, removed, and hammered into shape.

Investigation of the puddling process reveals that there are three steps in the formation of wrought iron:

(1) Melting and removing the impurities from the iron.
(2) Producing the proper slag and maintaining it in the molten state.
(3) Granulating the iron and mixing it with the proper amount of slag.

James Aston discovered that these steps could be done separately, thereby permitting much better control over the process. In the *Aston process* the pig iron is melted in a cupola, then drawn off into ladles where the sulphur is removed, and finally refined in a Bessemer converter. Concurrently, the proper slag is prepared in an open-hearth furnace and is then poured into a ladle. In the third step, the molten iron is poured into the slag at a given rate, and because the slag is cooler than the iron, the iron immediately solidifies. The hardening frees dissolved gases rapidly enough to cause small explosions which shatter the iron into small particles. The surplus slag is then poured off, leaving a spongy mass of iron intimately mixed with molten slag. This mass is next placed in a press, which forces out the surplus slag, welds slag-coated iron particles together, and leaves a solid bar of 6000 to 8000 pounds called a *bloom*. Wrought iron is claimed to have good corrosion-resistance properties because of the slag coating on the iron particles.

Copper. Since there are a large number of important copper ores and a correspondingly large number of methods of extracting copper from its ore, the metallurgy involved is very complex. The more important ores are native copper, carbonates, oxides, and sulphides.

Native copper is obtained from its ore by heating finely crushed ore in a furnace until the copper melts and flows to the bottom, where it is drawn off. To be of commercial use, this copper has to be refined.

The copper ores containing oxides and carbonates are processed in a reverberatory furnace, where unburned gases combine with the oxygen and the carbonates. The product must be refined.

Copper sulfide ores are first crushed, then roasted in the presence of oxygen until most of the sulphur has been displaced by oxygen to make a copper oxide. The oxide is reduced in a reverberatory furnace to a *matte*, which still contains some sulphur and iron. The matte is next heated in a converter, much like a Bessemer converter, where air is forced through the molten material until the sulphur leaves as sulphur dioxide and the iron becomes iron oxide. The iron oxide is removed when it combines with the silica lining of the converter. The resulting blister copper is about 99% pure, which is sufficiently refined for many purposes. However, slight impurities greatly affect the electrical properties of copper; therefore, further refining is necessary for current-carrying coppers.

Copper is now largely refined by *electrolysis*. Thin sheets of pure copper form the cathodes, and thick sheets of unrefined *blister copper* are the anodes; a solution of copper sulphate is the electrolyte. The pure and blister copper sheets are hung alternately in the tank: direct current passes between them carrying pure copper from the blister sheet to the pure sheet, where it is deposited. The impurities, including gold and silver, drop to the bottom of the tank, from which they are salvaged. Often there is enough of the precious metals to pay for the whole refining process.

Aluminum. Although there are several ores of aluminum, the only one of commercial value is *bauxite*. Bauxite, a compound of aluminum, oxygen, and chemically combined water, is usually found with iron oxide, silicon oxide, and titanium oxide as impurities. Of all the metallic elements in the earth's crust, aluminum is the most abundant, constituting about 8% of the surface layer.

The production processes of aluminum are the reverse of those of most metals. The usual procedure is first to remove the metal from the ore and then to purify it, but with aluminum the impurities must be removed first, since the oxides of the impurities would be reduced as well as the aluminum oxide during the final reduction process.

In the most commonly used process for refining bauxite, the ore is crushed and finally ground to a powder. The powder is mixed with a hot solution of sodium hydroxide and pumped into large pressure tanks called *digesters*. In the digesters, the sodium hydroxide dissolves the aluminum hydroxide out of the bauxite, producing a solution of sodium aluminate:

$$AL(OH)_3 + NaOH = NaAlO_2 + 2H_2O$$

The impurities, which remained solid, are filtered out as the sodium aluminate solution is pumped from the digesters.

The hot sodium-aluminate solution is next pumped into very tall precipitating tanks (50 feet and more) where fine crystals of aluminum hydroxide settle out as the solution cools, leaving sodium hydroxide:

$$NaAlO_2 + 2H_2O = Al(OH)_2 + NaOH$$

The aluminum hydroxide is transferred to other tanks, where it is washed; the sodium hydroxide is pumped back into the digesters for reuse. The aluminum hydroxide is heated to a high temperature, which drives off the water and leaves aluminum oxide (Al_2O_3).

The reduction of Al_2O_3 is an electrolytic process which is carried on in cells built of steel and lined with carbon (Fig. 1-6). The electrodes are large blocks of carbon which are hung in the cells. Each cell is able to produce about 250 pounds of aluminum per day.

Cryolite, which can be found naturally only in Greenland, but which can be produced chemically, is the electrolyte. In starting the process, the cell is nearly filled with cryolite, and the electricity is turned on until the cryolite is melted. As soon as the electrolyte is molten, aluminum oxide is added and dissolves in the cryolite. The electric current then breaks up the Al_2O_3 into aluminum and oxygen. The oxygen is freed at the carbon anodes and the aluminum is deposited in a molten state on the bottom of the cell. The molten aluminum is drawn off frequently and more aluminum oxide is added. The cryolite remains unchanged throughout the process and is used over and over.

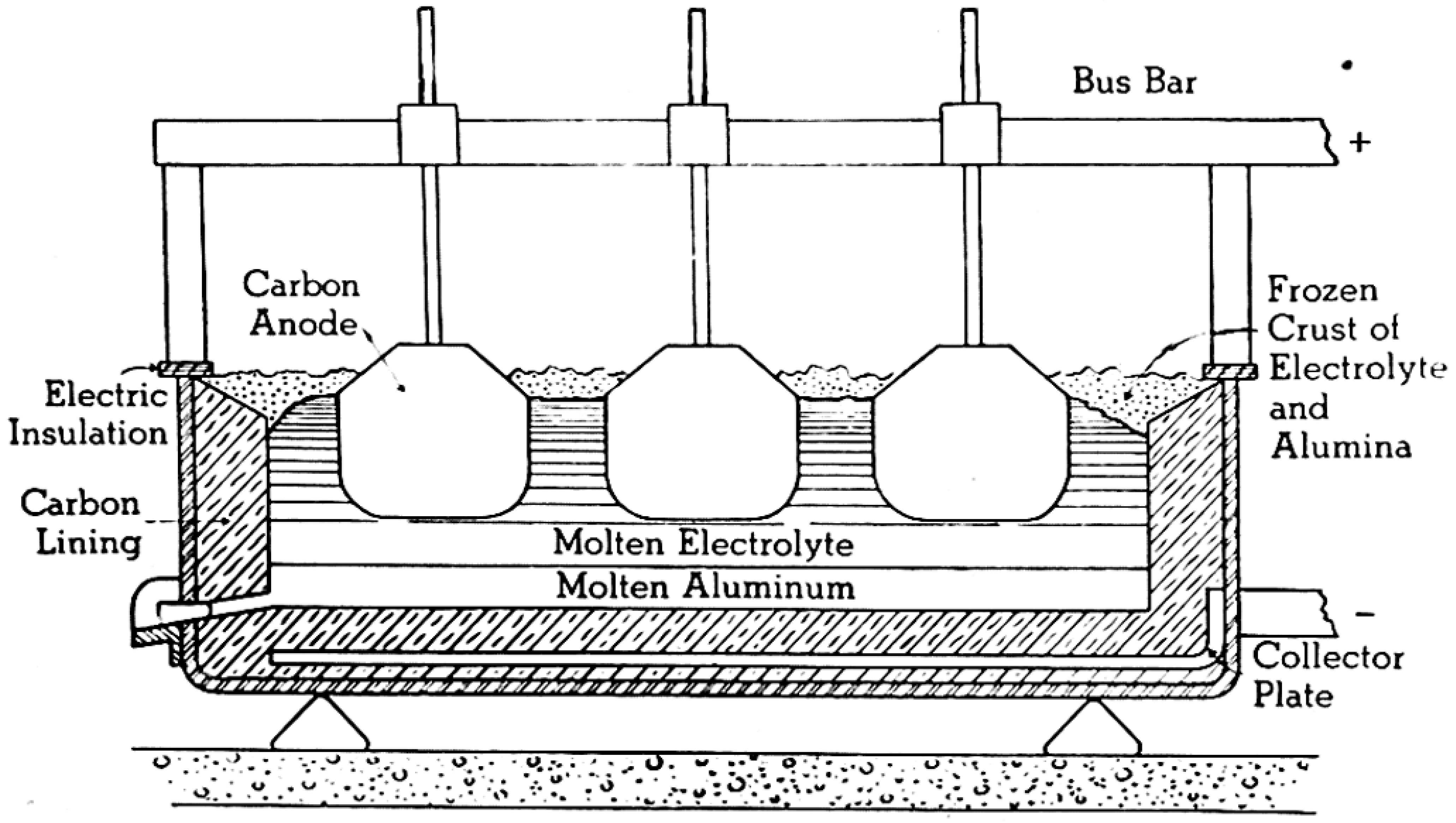


Fig. 1-6. The Hall-Héroult electrolytic cell. *Courtesy Aluminum Company of America.*

The molten aluminum is drawn off and is poured into molds to form bars, which are called *pigs*. The pigs contain some impurities which may be eliminated by remelting and pouring into other molds.

The use of aluminum has grown tremendously with the great reduction in price. It finds its greatest use where lightness, electrical conductivity, heat conductivity, or corrosion-resistance is of major importance.

Magnesium. Magnesium constitutes about 2 % of the earth's crust. Although it is found in many compounds, the main sources are magnesium chloride, which is a by-product of the refining of salt from the brine wells in Michigan, and magnesite.

The base material for electrolysis is magnesium chloride, which is obtained from the brine in a very pure condition, or by chlorinating the magnesite. The electrolytic method consists of the electrolysis of molten magnesium chloride either by itself or mixed with other molten chlorides to lower the melting point. There are other less used methods for processing the more uncommon ores.

Definitions and Summary

The usual procedure in obtaining a useful metal from an ore is:

(1) Extraction of the desired metal from other materials.
(2) Refinement of the metal.
(3) Addition of alloying elements.

(There are exceptions to the above order, such as in the case of aluminum, where steps 1 and 2 are reversed.)

Ore is metal in its natural state, and it is usually thought of as metal of commercial value.

Gangue is the earthy material which is mined with the ore.

Smelting is melting an ore to isolate and refine it.

Flux is a material used to promote the fusion of other materials.

Reduction is decreasing of the oxygen content of a compound.

Oxidation is increasing the oxygen content of a compound.

Slag is the refuse matter which is separated from metals during the smelting process.

Pigs are bars of metal cast directly from the smelting furnace.

Pig iron is iron in the form of pigs.

Steel is a variety of iron containing from about 0.1% to 1.6% carbon.

Cast iron is a variety of iron containing about 3.5% carbon; it is not appreciably malleable at any temperature.

Ingots are bars of metal which have been cast into ingot molds.

Acid steel is steel melted in a furnace having an acid lining and a siliceous slag.

Basic steel is steel melted in a furnace having a basic lining and a basic slag.

An **acid** is an oxide of a non-metal.

A **base** is an oxide of a metal.

Gray cast iron is cast iron containing free carbon.

White cast iron is cast iron containing no free carbon.

Reverberatory means heating by reflected heat or by radiation from the roof of the furnace.

Coke is the solid left after the volatile gases have been driven from a caking coal. It consists mainly of carbon.

A **bloom** is a large bar of steel formed directly from an ingot by hammering or rolling.

Electrolysis is the chemical decomposition of a compound by the action of an electric current.

PROBLEMS

1. Discuss fully why so much steel is made by the open-hearth process in the United States.
2. What parts do oxygen and carbon play in the blast furnace? In the open-hearth furnace? In the Bessemer converter?
3. Why is iron oxide mixed with the molten metal in the open-hearth furnace?
4. Design a chart showing the steps in the manufacturing of steel by the open-hearth method. Start with ore and other raw materials.
5. Compare the qualities of the steel made by the open-hearth, Bessemer converter, and electric furnace methods.
6. Describe the methods of refining copper.
7. Why must aluminum companies be located near great sources of electrical energy?
8. How do the electrolytic processes for aluminum and copper differ?
9. List some common uses of copper, magnesium, aluminum, open-hearth steel, electric steel, and Bessemer steel.
10. Compare the puddling and Aston processes of making wrought iron.
11. Describe the process of making malleable cast iron. Why is it more useful than cast iron in certain cases?
12. Why did magnesium become so important a metal during World War II?

Chapter 2

MECHANICAL PROPERTIES OF MATERIALS

AN ENGINEER, in order to describe a material or what happens to a material during a given process, must use well-defined words which indicate clearly the properties of one material as distinguished from all others. This chapter will define the more important terms as used in metallurgy.

Metallurgy. Metallurgy may be defined as the science which deals with the preparation of metals from raw materials and the adaptation of these metals to special purposes. Fundamentally, it is a specialized application of the sciences of physics and chemistry.

Stress. Stress may be defined as the internal resistance to the deforming effects of an external force. The resistance is caused by the attractive forces between the molecules of the material; these forces attempt to keep the positions of the molecules unchanged. There are three general types of stress:

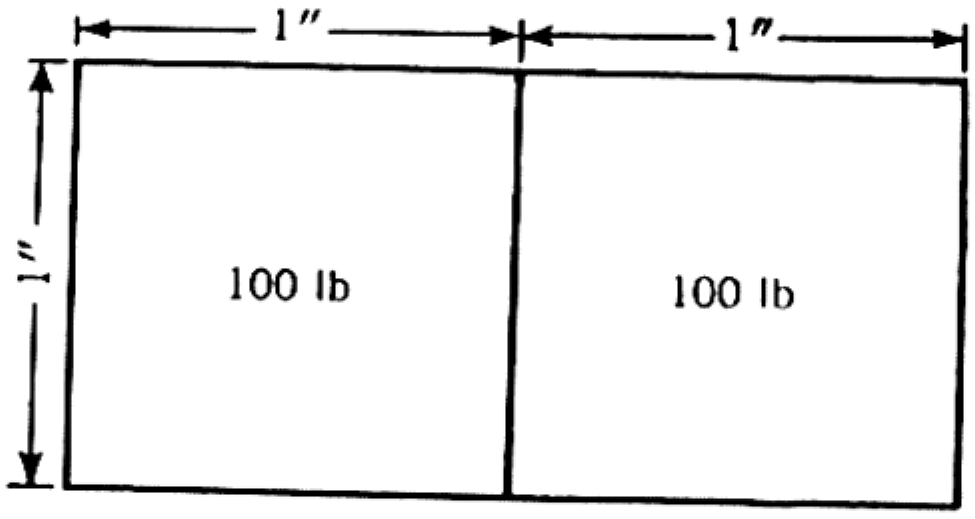


Fig. 2-1. Relationship between unit stress and total stress.

(1) *Tension.* When a member (rod, bolt, etc.) resists a pull on each end.

(2) *Compression.* When a member, such as a column, resists a push on each end.

(3) *Shear.* When two parallel forces in nearly the same plane of action act toward each other upon a member. This type is best illustrated by a pair of scissors.

Stress or unit stress. The internal resisting force of a material per unit of area. Figure 2-1 shows the cross sections of two one-inch squares. On each square there is a force of 100 pounds. The stress is 100 pounds per square inch (100 psi), and the total stress is 200 pounds. This relationship may be expressed as an equation:

$$P = SA$$

where P = total stress
S = stress (sometimes unit stress)
A = area

By stating the stress rather than the total stress when describing a metal, it becomes much easier to make comparisons.

Example: What would be the stress in a two-inch diameter rod supporting 45,000 pounds?
Solution:

$$S = \frac{P}{A}$$

$$S = \frac{45{,}000 \text{ lb.}}{\frac{\pi}{4}\, 2^2 \text{ in.}^2} = 14{,}000 \text{ psi}$$

Strength. The maximum stress which a material may withstand. Statement of the strength of a material should specify the type of stress, because the values of tensile, compressive, and shear stresses may differ widely.

Stiffness. The property of a material which enables it to resist a change in shape, as for example, the bending of a beam.

Elasticity. The ability of a material to regain its original shape after having been distorted.

Plasticity. The opposite of elasticity: that is, the inability of a material to regain its original shape after having been distorted.

Strain. When a force of any kind is applied to a material it changes shape. The total deformation is called the *total strain;* the deformation per unit of length is called the *strain.* If a material is under a tensile stress the strain is called *elongation.*

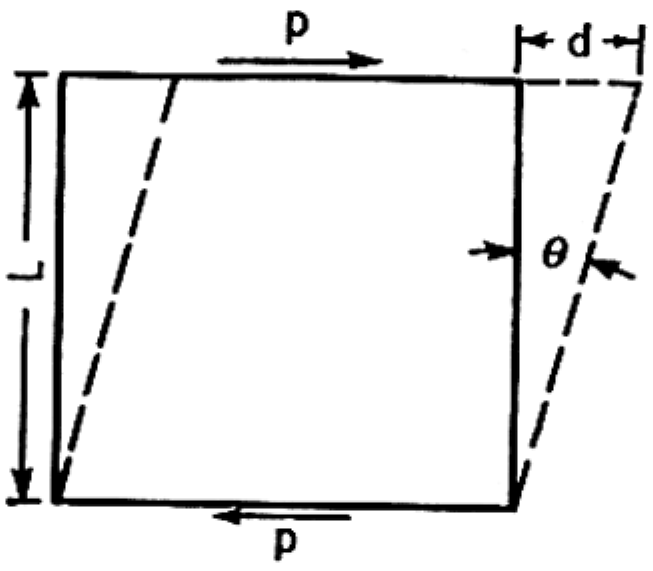


Fig. 2-2. Shear relationships.

Example: A two-inch test specimen has been deformed until it is 2.16 inches long. What is the total elongation? The unit elongation?
Solution:

$$\text{Total elongation} = 2.16 \text{ in.} - 2.00 \text{ in.} = 0.16 \text{ in.}$$

$$\text{Unit elongation} = \frac{0.16 \text{ in.}}{2 \text{ in.}} = 0.08 \text{ in./in.}$$

Shear stresses cause a shear strain, which is measured differently from a strain caused by tensile or compressive stresses. Figure 2-2 shows two equal and opposite forces, P, with a distance, L, between their lines of action. The block has been deformed to the shape shown by the dotted lines.

The total shear strain is d and the unit shear strain is d/L. In the figure, $d/L = \tan\theta$. Since θ is very small, the $\tan\theta$ is numerically approximately equal to θ in radians. The shear strain may then be expressed as the angle in radians. The angle of twist in a shaft under a torsional load is the shear strain.

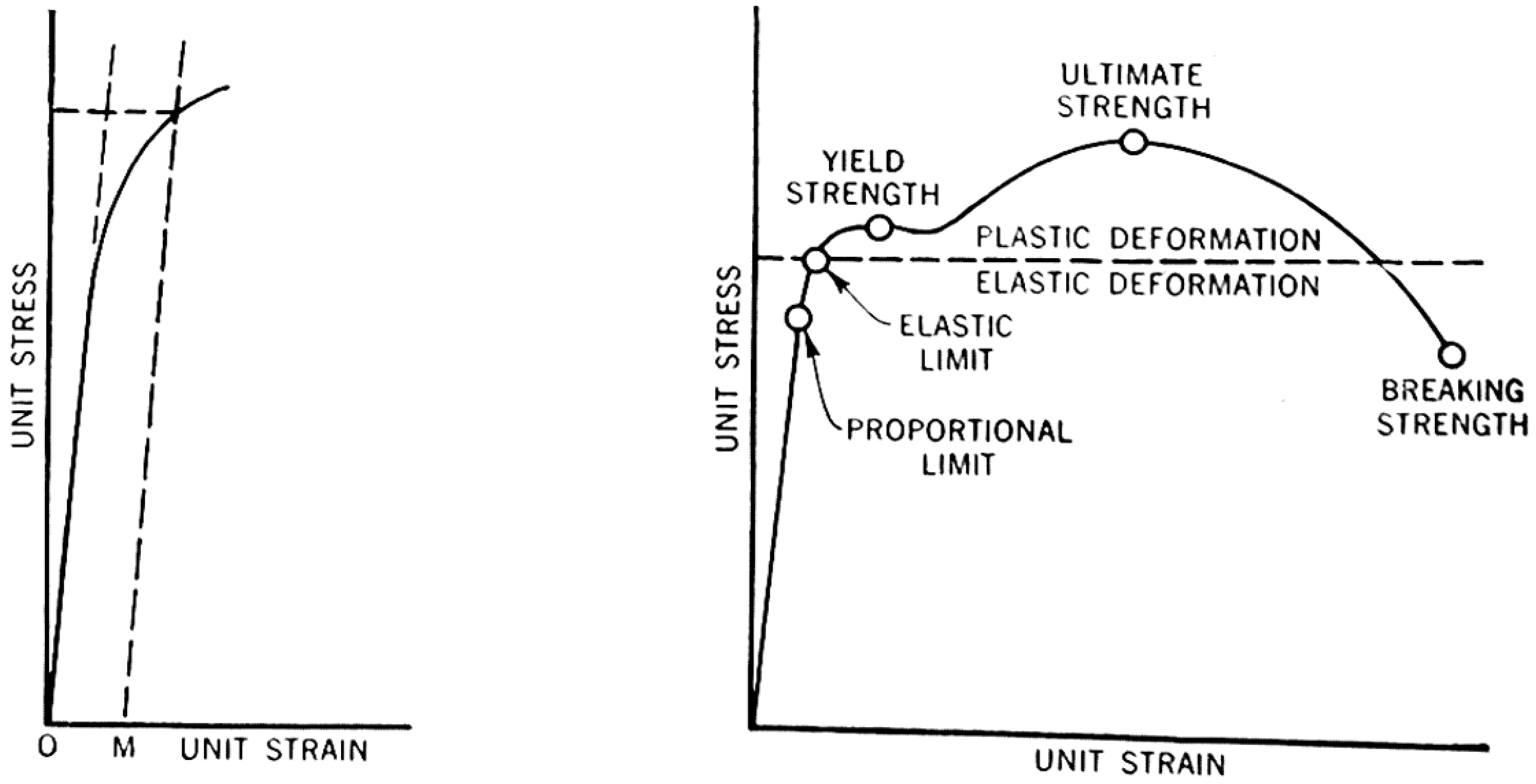
Example: If $L = 10$ in. and $\theta = 0.1$ deg in Figure 2-2, what would the unit strain be?

Solution:

$$\theta = d/L$$

$$\text{Total strain} = d = 6L = 0.00175 \text{ rad} \times 10 \text{ in.} = 0.0175 \text{ in.}$$

The stress-strain diagram. When materials are subjected to increasing stresses until rupture occurs, and the strain is noted at several stresses, the resulting data may be plotted to show typical stress-strain diagrams as in Fig. 2-3. The first part of the curves are straight lines, showing that the stress is proportional to the strain. The upper limit of the straight line is called the proportional limit. The curve between the origin and the proportional limit follows Hooke's Law, which states that *below the proportional limit, the stress varies as the strain.*



(a) (b)

Fig. 2-3. Stress-strain diagrams.

Elastic limit. The point beyond which a further strain will cause a permanent deformation. Up to the elastic limit the material is elastic and beyond that point it is plastic.

Yield strength. The stress at which, in soft steel, there is an increase in strain with no increase in load. (Fig. 2-3b.) In cast metals and the harder steels, the yield strength is the stress which corresponds to a specified permanent strain, such as M in Fig. 2-3a, where OM is the specified permanent strain.

Ultimate strength, or **strength.** The greatest stress that a material may undergo without rupture. Beyond this point the material may elongate with a corresponding decrease in cross-section area, thus causing a reduction in the load which may be applied. If the elongation continues, the material will rupture at the *breaking point.* The part of the curve between the ultimate stress and the breaking point can be obtained only when the strain is controlled. In Fig. 2-3a, the ultimate strength and the breaking strength are the same.

Modulus of elasticity, or **Young's modulus.** The slope of the curve between the proportional limit and the origin. It is equal to the stress divided by the strain:

$$E = \frac{\text{stress}}{\text{strain}} = \frac{S}{\delta}$$

The values of the modulus of elasticity for most materials are given in many handbooks. This modulus is a measure of stiffness: the higher the values the stiffer the material.

Modulus of rigidity, or **shear modulus.** **(E_s.)** The value of the slope when the shear stress is plotted against the shear strain. Its value differs from that of the modulus of elasticity.

Example: If $E = 30{,}000{,}000$ psi for steel, and if a piece of steel whose cross-section area is 3 sq in. and whose length is 10 in. is loaded with 90,000 lb, what is the total elongation?

Solution:

$$E = \frac{S}{\delta}$$

$$S = \frac{90{,}000 \text{ lb}}{3 \text{ in.}^2} = 30{,}000 \text{ psi}$$

$$\delta = \frac{30{,}000 \text{ psi}}{30{,}000{,}000 \text{ psi}} = 0.001 \text{ in./in.}$$

$$\text{Total strain} = 0.001 \text{ in./in.} \times 10 \text{ in.} = 0.01 \text{ in.}$$

Hardness. The ability of a material to resist abrasion or indentation. The most common methods of measuring hardness depend upon indentation. The *Brinell hardness number* is the ratio of the area of the indentation caused by a 10 mm dia ball to the load in kilograms resting on the ball. The *Rockwell hardness number* is dependent upon the depth of an impression made by a standard point under a standard load.

Machinability. The readiness with which a material may be cut with a tool. This property has no definite scale of measurement except that of experimental comparison.

Malleability. The property which determines the ease with which a material may be rolled or hammered into a new shape without rupture. This may be partially indicated by the ultimate strength under impact.

Toughness. The ability of a material to be forced into new shapes under great stress without rupture. It may be indicated by measuring the work per unit of volume necessary to cause rupture.

Ductility. The ability of a material to be drawn out without rupture. Ductility can be measured by bending or by the *percent elongation.*

$$\text{Percent elongation} = \frac{\text{total strain at rupture}}{\text{original length}} \times 100$$

The cross-section area of a ductile material may have a large reduction at the point of rupture. The *percent reduction of area* is also an indication of the ductility of a material.

$$\text{Percent reduction of area} = \frac{(\text{original area} - \text{area at rupture})}{\text{original area}} \times 100$$

Example: A 2-in. test specimen having a diameter of 0.505 in. was ruptured in a testing machine. The length after rupture was 2.3 in. and the diameter at the point of rupture was 0.35 in. Find the percent elongation and the percent reduction of area.

Solution:

$$\text{Percent elongation} = \frac{2.3 - 2}{2} \times 100 = 15\%$$

$$\text{Percent reduction in area} = \frac{(0.505)^2 \frac{\pi}{4} - (0.35)^2 \frac{\pi}{4}}{(0.505)^2 \frac{\pi}{4}} = 52\%$$

Creep. At high temperatures metals tend to flow or creep very slowly when under stresses which would cause a constant strain at room temperatures. It might take months or years to produce a damaging deformation. This property must be considered when designing high-temperature equipment such as valves, steam turbines, and jet engines. The designer should know the deformations produced by given stresses and the allowable creep: in other words, the *creep limit.*

Fatigue. Failure of a material due to fatigue is caused by applying a sufficient number of cycles of stress when the stress is larger than the *fatigue* or *endurance limit.* The endurance limit is the limiting stress below which a metal will withstand an indefinitely large number of cycles of stress.

Temperature stresses. When many metals are heated they tend to expand, but if the length is fixed, a stress will be set up equal to that necessary to compress the material a distance equivalent to that which it would have expanded. The stress can be expressed by the following relationship:

$$S = ctE$$

where S = stress (psi)
c = coefficient of linear expansion
t = temperature change (°F)
E = modulus of elasticity

Example: Find the unit stress in a 30-ft. steel rail if the temperature change is 100 F and the ends are fixed. $E = 30{,}000{,}000$ psi; $c = 0.000007$.

Solution:

$$S = 0.000007 \times 100 \times 30{,}000{,}000 = 21{,}000 \text{ psi}$$

Crystallization. Some substances in changing from a liquid to a solid state solidify in discontinuous masses having a definite shape and color; these masses are called *crystals.* Molecules must be free to arrange themselves in definite patterns in order to form crystals, such as when they are in a liquid or a solid solution, or in the molten state. Imperfect crystals or *grains* are formed when the metal is in a plastic state, since the molecules do not have complete freedom of movement in arranging themselves.

SUMMARY

Metallurgy is the science which deals with the preparation of metals and their adaptation to special uses.

Stress is the internal resistance to the deforming effect of an external force. The three fundamental types are tension, compression, and shear.

Strength or **ultimate strength** is the maximum stress a material may withstand.

Unit stress or **stress** is the stress per unit of area.

Stiffness enables a material to resist a change in shape.

Elasticity is the ability of a material to regain its shape after the release of a deforming force.

Plasticity is the opposite of elasticity.

Strain is the deformation of a material under load.

Unit strain or **strain** is the strain per unit of length.

The stress-strain diagram is a plot of stress vs. strain.

Yield strength is the stress which corresponds to a specified permanent strain.

Proportional limit is the stress beyond which Hooke's Law does not apply.

Elastic limit is the stress beyond which further strain will cause a permanent deformation.

Modulus of elasticity is the stress divided by the strain.

Hardness is the ability of a material to withstand abrasion or indentation.

Machineability is the readiness with which a material may be cut by a tool.

Malleability is the ease with which a material may be rolled or hammered into a new shape.

Toughness is the ability of a metal to be forced into new shapes under great stress.

Ductility is the ability of a metal to be drawn out.

Creep is the slow flow of stressed metals at normal or elevated temperatures.

Fatigue is the failure of metals because of repeated stress cycles.

PROBLEMS

1. A steel rod $\frac{3}{4}$ in. in diameter is subjected to a tensile stress of 30,000 psi. What is the pull on the rod?

2. The tensile load on a bar is 50,000 lb. What is the stress in the bar if the cross-section area is 3 sq in.?

3. The diameter of a standard tensile test specimen is 0.505 in. If the testing machine indicates a pull of 6,000 lb, what is the stress?

4. What load can be supported by a short steel block, 6 in. by 6 in., if the safe compressive stress is 10,000 psi?

5. The ultimate stress of a certain steel is 100,000 psi. At what load would a 2-in.-dia rod fail?

6. A metal shears is cutting a sheet of copper $\frac{1}{8}$ in. thick and 4 ft wide. What force is on the blade if the blade cuts the full width at once and the ultimate shear stress of copper is 20,000 psi?

7. A punch press is punching a 4-in.-dia hole from a piece of brass $\frac{1}{4}$ in. thick. If the ultimate shear stress of brass is 22,000 psi, what force is the press exerting? (*Note:* Use the circumferential area.)

8. A standard test specimen has a gage length of 2 in. After rupture the length is 2.30 in. What is the unit elongation?

9. In Problem 8, what is the percent elongation?

10. If the strain for a 2-in. specimen is .005, what is the total length when loaded?

11. The strain for an 8-in. specimen is 0.006 in. per in. What is the loaded length?

12. What is the modulus of elasticity of a material that has a strain of 0.002 in. per in. when the stress is 60,000 psi?

13. A material with a modulus of elasticity of 20,000,000 psi is loaded until the strain is 0.001 in. per in. What is the stress in the material?

14. What is the loaded length of a 10-ft rod if the stress is 5000 psi and the modulus of elasticity is 16,000,000 psi?

15. Discuss the practical uses of the stress-strain diagram.

16. What would be the outstanding properties of a metal to be used for each of the following purposes?

a. Engine crankshaft
b. Turbine shaft
c. Transmission gears
d. Piano wire
e. Razor blade
f. Punches and dies

17. If the original diameter of a test specimen is 0.505 in. and the diameter after rupture is 0.35 in., what is the percent reduction in area?

18. In Fig. 2-2, if $d = .01$ in., and $L = 2$ in., what is the shear strain and what is the angle θ in radians?

Chapter 3

THE FABRICATION OF METALS

Numerous methods exist of forming metals into the final, useful shape; each method has its special applications and its effects upon the properties of the metal. This chapter deals with many of the fabricating methods; powder metallurgy and welding will be discussed in separate chapters.

Casting. Casting is the solidification of materials in molds. It involves pattern design, the making of patterns, the making of molds, and the pouring of the metal. The production of good castings depends upon co-operation between the designer and the foundryman, since many of the controlling variables involve both. Some of these variables are:

(1) The great proportion of handwork in some types of casting.
(2) The need for strict control of alloy composition and pouring temperatures.
(3) The type of foundry equipment available.
(4) The molding material available.

The total cost of the casting should be the criterion for choosing the method rather than the cost of any one particular operation, for an increase in the cost of one operation may be more than offset by a resulting decrease in the cost of another.

Pattern design. Patterns are approximate models of the desired casting. They are made of any easily shaped material. The usual material is wood, but if production figures warrant, several metal patterns may be cast from one wooden pattern.

Molds are separated as shown in Fig. 3-1. The bottom part is the *drag*, the top part the *cope;* together they form the *flask*. The cope and the drag are made separately and then placed together, lined up by the pins and ears. Consequently, for easy mold-making the parting line should be a plane surface; the part should therefore be designed to make such a surface possible, as is illustrated in Fig. 3-2. Many times it may pay to redesign a part in order to cut production costs.

Locating points, which are points for locating the pattern in the mold, should all be on one side of the parting line and as far apart as possible. They should also be placed at points of close tolerance. *Core prints* should be large enough to hold the cores in place when the metal is being poured and should be extra large if there is an overhang on the core. *Cores* are mold parts for shaping the interior of a casting; *core prints* are cavities in the cope or drag which hold the core in place.

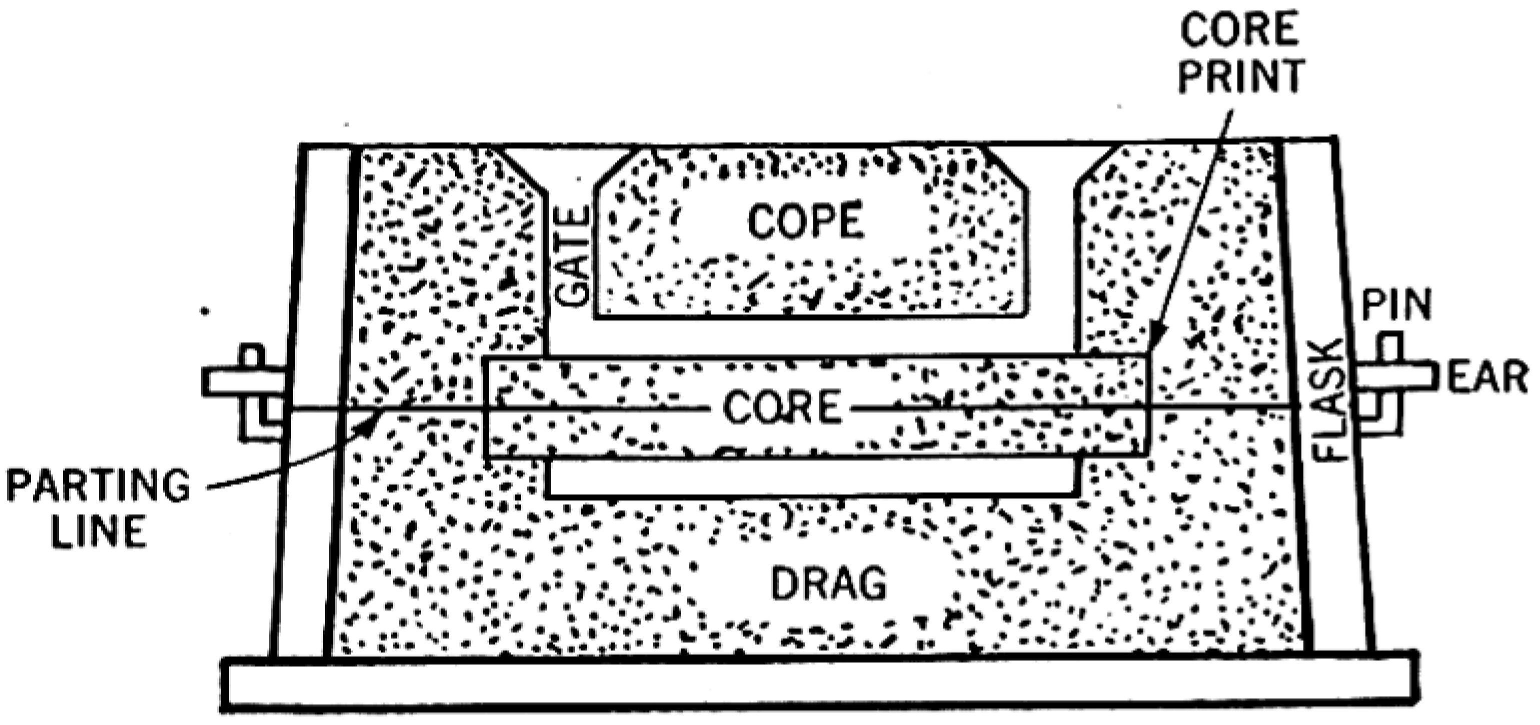
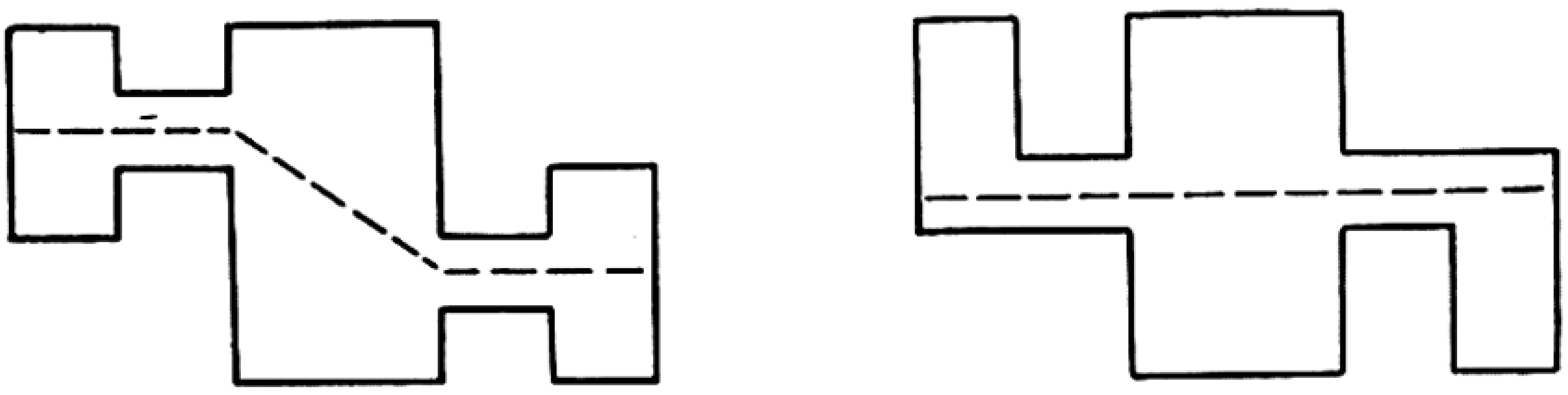


Fig. 3-1. Sand mold.



Wrong Right

Fig. 3-2. Wrong and right parting line.

Several allowances can be made when the patterns are formed which will offset predictable changes in the metal as it cools. Since most metals shrink as they cool, the pattern should be made large enough to offset the shrinkage of a particular metal. This shrinkage factor also complicates the design of the part, since most mold materials do not shrink. For instance, if there are two projections on one side of a piece (Fig. 3-3), the metal in between the projections cannot contract because of the mold. Therefore it will have a residual stress when cold, thus weakening the part. Predictable distortion can also be compensated for, with some such device as a U-section which opens on cooling. The vertical sides of a pattern should be tapered slightly for easy removal from the mold.

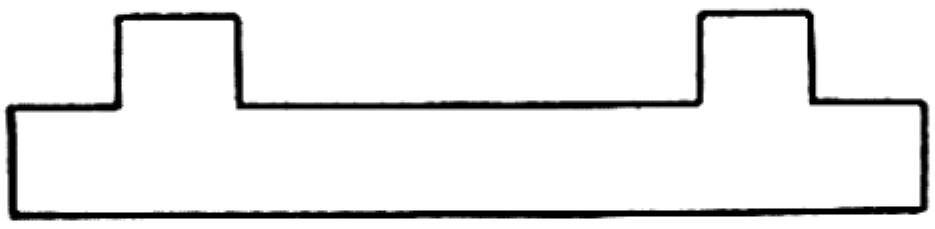


Fig. 3-3. Flanges cannot contract because of mold.

This is called *draft*. Usually castings need cleaning, and if they are to fit other parts they need machining. Therefore, the pattern should be made large enough to allow the removal of some metal.

Casting design. Castings should be designed to provide the following:

(1) All parts can be molded and poured easily.

(2) The mold can be fed from one riser or gate located at the highest point. If there are points higher than any riser, air pockets may be formed.

(3) Solidification can start at the bottom and rise regularly to the feeding gate.

It is desirable to use metals of a low melting point so that solidification will be slow. When high-melting-point metals are used, the cooling is fast, because of the great difference in temperature. Thin sections are hard to cast with a fast-cooling metal since some parts may solidify before others. Consequently, large residual stresses are set up which produce a tendency to crack.

Since a volumetric shrinkage occurs, large risers should be provided as a reservoir of molten metal. The strength just below the freezing point of the metal is low; therefore cracks may occur due to the resistance to contraction of the mold. This trouble can be avoided by good casting design.

Casting defects. Many casting defects may be eliminated by careful design, but those which cannot be thus eliminated must be allowed for. Such weaknesses are blowholes, slag inclusions, center-line weaknesses, hot tears, and shrinkage cavities.

Blowholes are caused by gas bubbles which cannot escape. Proper design of the casting to make sure all gas can escape through a riser, and the use of the proper sand in sand molds to allow gas to pass into the mold, will help to eliminate blowholes. *Slag inclusions* can best be eliminated by pouring slag-free metal. Sometimes slag can be skimmed off in the ladle.

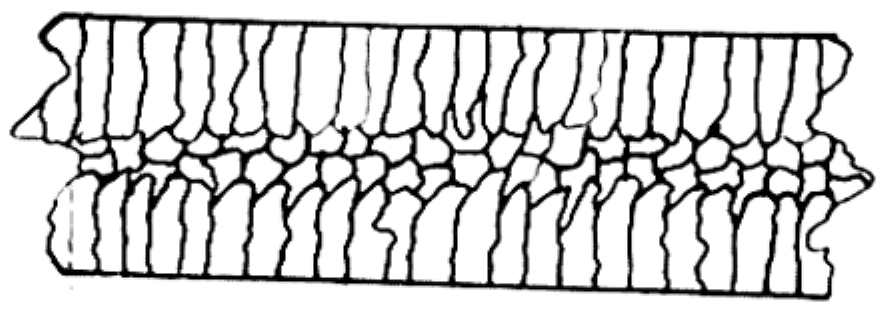


Fig. 3-4. Center-line weakness.

Figure 3-4 shows the grain formation in the cross section of a thin-cast piece. The grains start forming on the surfaces and grow toward the center where they meet end to end. Since the attraction between the ends is small, a weak center line is formed. The best way to eliminate this fault is not to have thin sections where strength is required.

Hot tears are caused by the solidification of one part of the casting before other parts, and by a design which does not allow contraction during cooling. They may be eliminated by using certain precautions such as:

(1) Uniform thickness or gradual changes in sections.

(2) Curved connecting members, such as curved spokes in a wheel. A curved member can bend, whereas a straight member must be compressed to be contracted, thus requiring a greater force.

(3) Fillets in corners where hot spots might occur. Figure 3-5 shows the grain formation in a sharp corner and a fillet corner. The reason for the ease of cracking in the sharp corner is that a weak line exists where the ends of the grains meet.

Shrinkage cavities are caused by a lack of metal. Many times these may be eliminated by having a sufficient supply in a riser, but there are times when they cannot be eliminated. At such times they must be taken into account in the design of the casting.

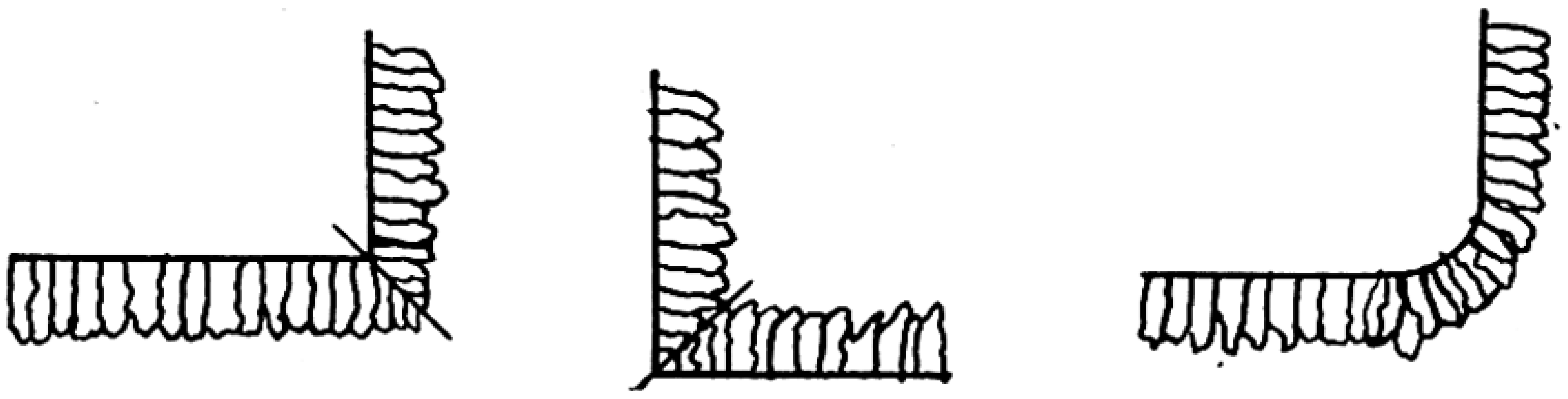


Fig. 3-5. How the fillet strengthens corner.

Sometimes weaknesses can be prevented by directional solidification. This can be accomplished by tapering in the right direction or by using *chills*. Chills are pieces of metal placed in the mold where cooling is to be accelerated. The metal can absorb more heat in a given time than the mold material.

Sand molds. The sand used in molds must have certain qualities in order to produce good castings:

(1) The sand must be refractory; that is, it must withstand high temperatures.

(2) It must be able to hold its shape under pouring conditions.

(3) It must allow heat to escape.

(4) It must be porous to allow the passage of gases.

The best sand is a spherical-grained quartz sand with a small amount of clay mixed in as a binder. The sand is rammed in the flask about the pattern by hand or by a molding machine which shakes the sand into place. The pattern must be removed very carefully in order to prevent damage to the mold. Cores are also made of sand, but they are usually baked to give them strength.

Plaster of Paris molds. These molds are made of plaster of Paris, fiber, an accelerator, and an excess of water. The excess of water causes small holes through the mold so that gases may escape. Plaster of Paris molds can be used up to temperatures of 2100 F. They have some advantages over sand molds when used within their temperature range:

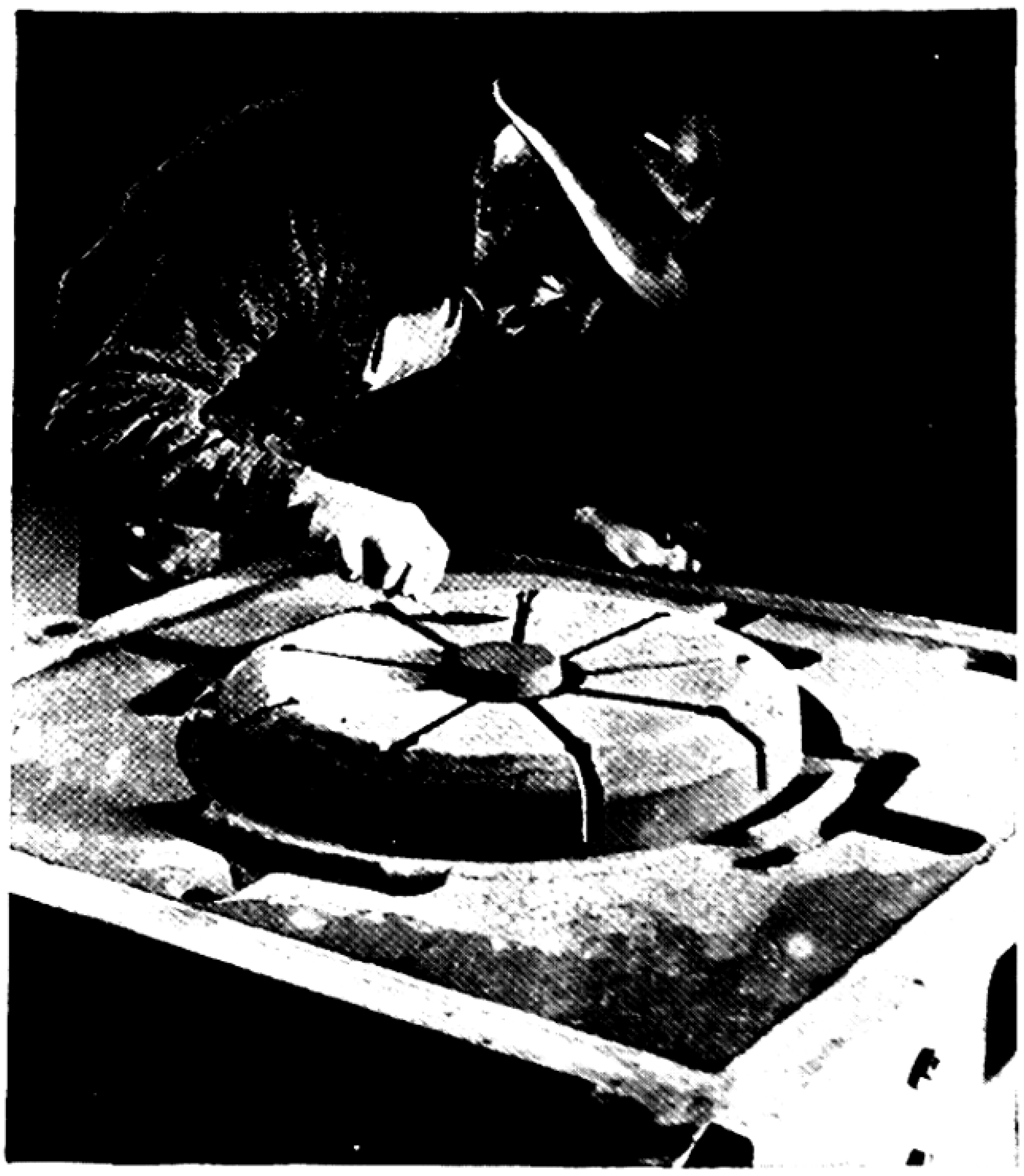


Fig. 3-6. Making a sand mold. *Courtesy Aluminum Company of America.*

(1) Smoother finish, which eliminates some machining.

(2) Closer dimensional tolerances.

(3) Finer detail and thinner sections, because of low heat conductivity.

(4) Greater solidity, because of slow cooling.

Plaster of Paris molds are used when few parts are required and when results equivalent to those of the higher-priced metal mold are desired. They are best used with brass or bronze plumbing, automotive hardware, and gears.

Fusible material castings. This is a very old process which has lately been used a great deal when complicated and close-tolerance castings are required. It was originally known as the *lost wax process.* The modern method uses low-melting-point metals rather than wax, since the metals are much stronger. The steps in the process are:

(1) Make an external plaster mold of the original.

(2) Close the mold and fill it with wax or metal.

(3) Pour out the liquid center after the surface has solidified. A thin shell is left whose thickness depends upon the cooling time.

(4) Put gates on the wax or metal.

(5) Pack the mold material around and in the new pattern.

(6) Bake until the mold is hard, then raise the oven temperature to melt out the pattern. The mold is now ready for use.

The lost wax method is often varied for special applications. To make complicated solid cores with curved holes, a model of the hole is made of some low-melting-point metal The sand is packed around and in the model. Then the model is baked at a temperature below its melting point. As soon as the sand is fully baked, the temperature is raised and the metal melts and flows out, leaving a curved hole.

Permanent mold castings. Permanent molds are used where production is high and rotary conveyors can be employed. The metals which are cast in this type of mold are, in order of importance, aluminum alloys, copper alloys, iron, and zinc. The molds are made of various metals, depending upon the casting metal. Bronze molds are used with low-melting-point alloys, whereas iron and steel molds are required for other non-ferrous metals. If iron is to be molded in a permanent mold, the mold must be lined with refractory material in order to prevent corrosion. The life of any of these molds depends upon the amount of corrosion and the finish required on the product.

An interesting type of permanent mold casting used for making such articles as toys and candle-sticks, where uniform thickness is not required, is the *slush casting*. The molten metal, usually zinc, is poured into the mold and allowed to harden until a sufficient thickness of solid shell is formed. The remaining liquid in the center is then poured out. A hollow casting is left.

A summary of the permanent molding process brings out the following points:

ADVANTAGES

(1) Dense, fine-grained product, free of holes.
(2) Low tool charges and good finish.
(3) Lower mold cost than for other metal-mold processes.
(4) Closer tolerances than with sand mold.

DISADVANTAGES

(1) Tolerances and thin sections not as good as with plaster of Paris and external-pressure molds.

(2) The zinc in high-zinc brasses makes zinc oxide on the mold, which spoils the finish on the casting.

(3) The production rate is lower than with die casting.

Semi-permanent mold castings. The general process is the same as for permanent mold castings except that sand cores are used. The use of sand cores reduces the production rate and gives poor dimensions about the core. This process is used for casting aluminum cylinder pistons and carburetors.

Die-casting. In die-casting, the metal is forced into a permanent, machine-operated mold under pressures up to 5000 psi. The melting chamber is part of the machine. The die or mold is made in two parts; one is stationary, and the other is moved automatically by the machine.

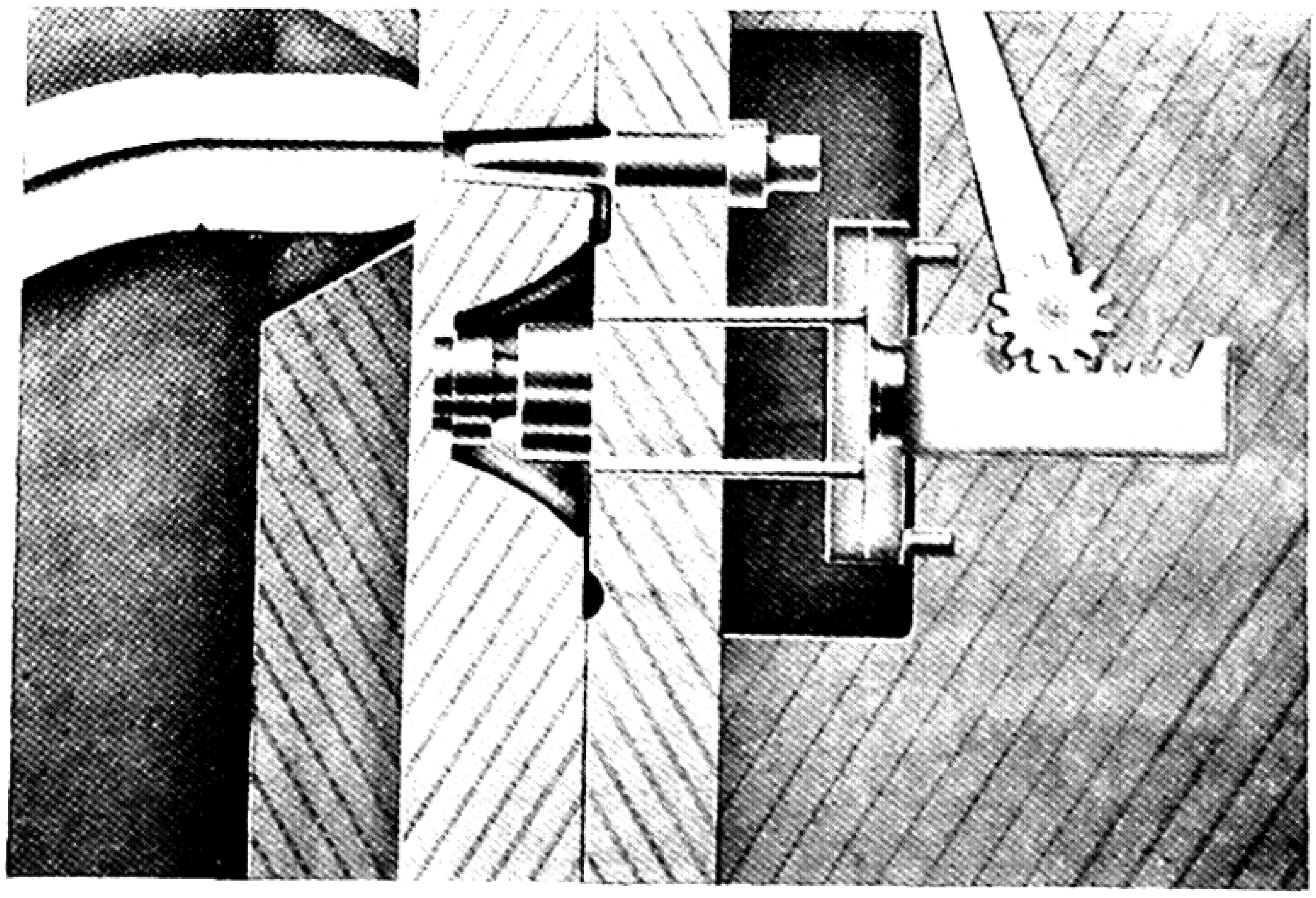


Fig. 3-7a. Here are two sections of a die closed and locked to receive from the pot the "shot" of metal to form a casting. *Courtesy The New Jersey Zinc Company.*

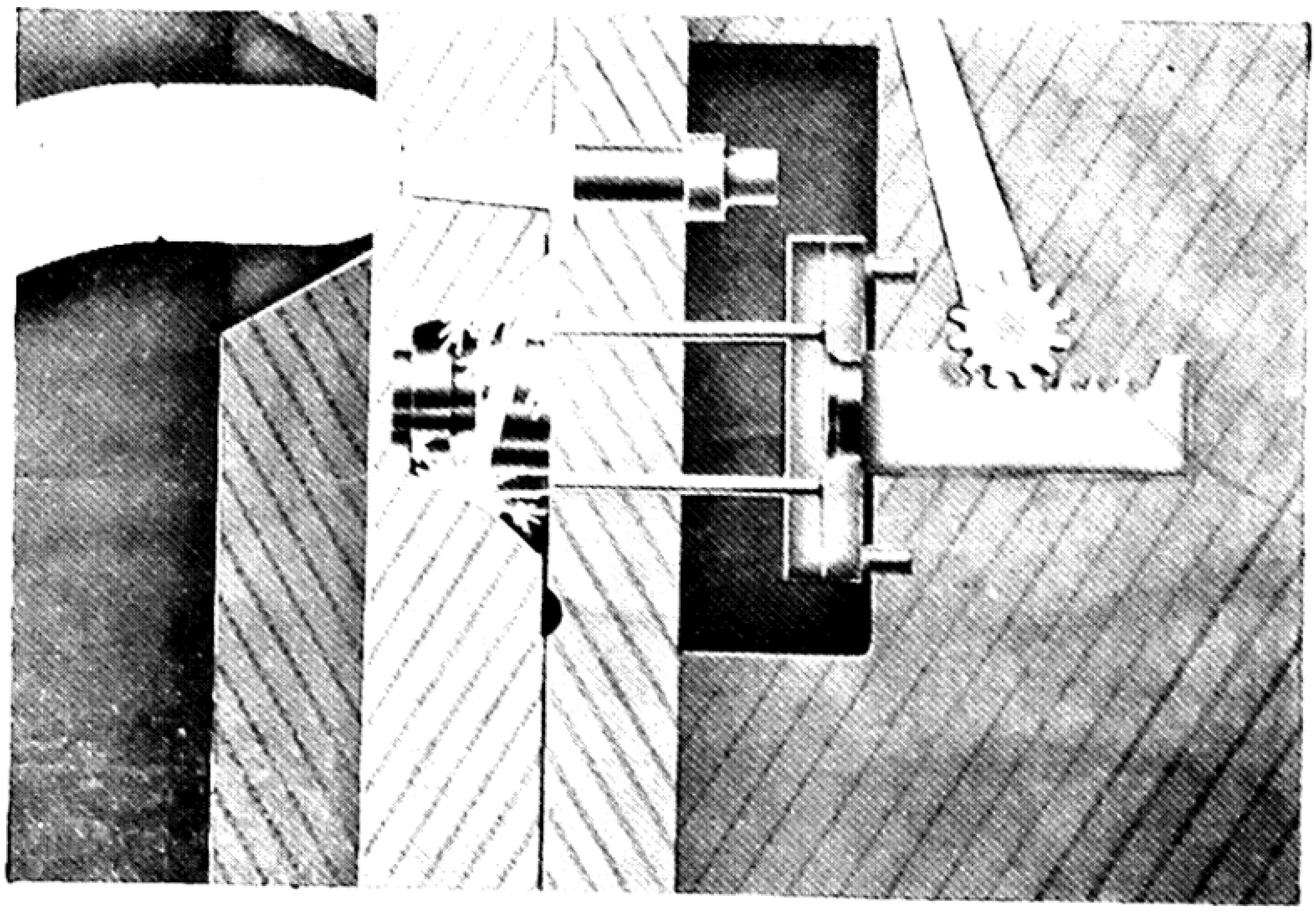


Fig. 3-7b. This drawing shows metal flowing into the cavity, which in these drawings is in the cover section of the die. *Courtesy The New Jersey Zinc Company.*

Castings are ejected from the mold by ejector pins which operate as the die opens. Aluminum and zinc alloys attack and corrode the pressure piston and cause serious trouble. *Cold-chamber casting* tends to eliminate this trouble, since the heating chamber is separated from the machine and only enough molten metal is placed in the well for one casting;

therefore, the piston is in contact with the metal only a short time. In this type of casting, pressures up to 20,000 psi are used, making more delicate shapes possible. The production time is longer than for straight die-casting, but the longer time is offset by a decrease in repair time.

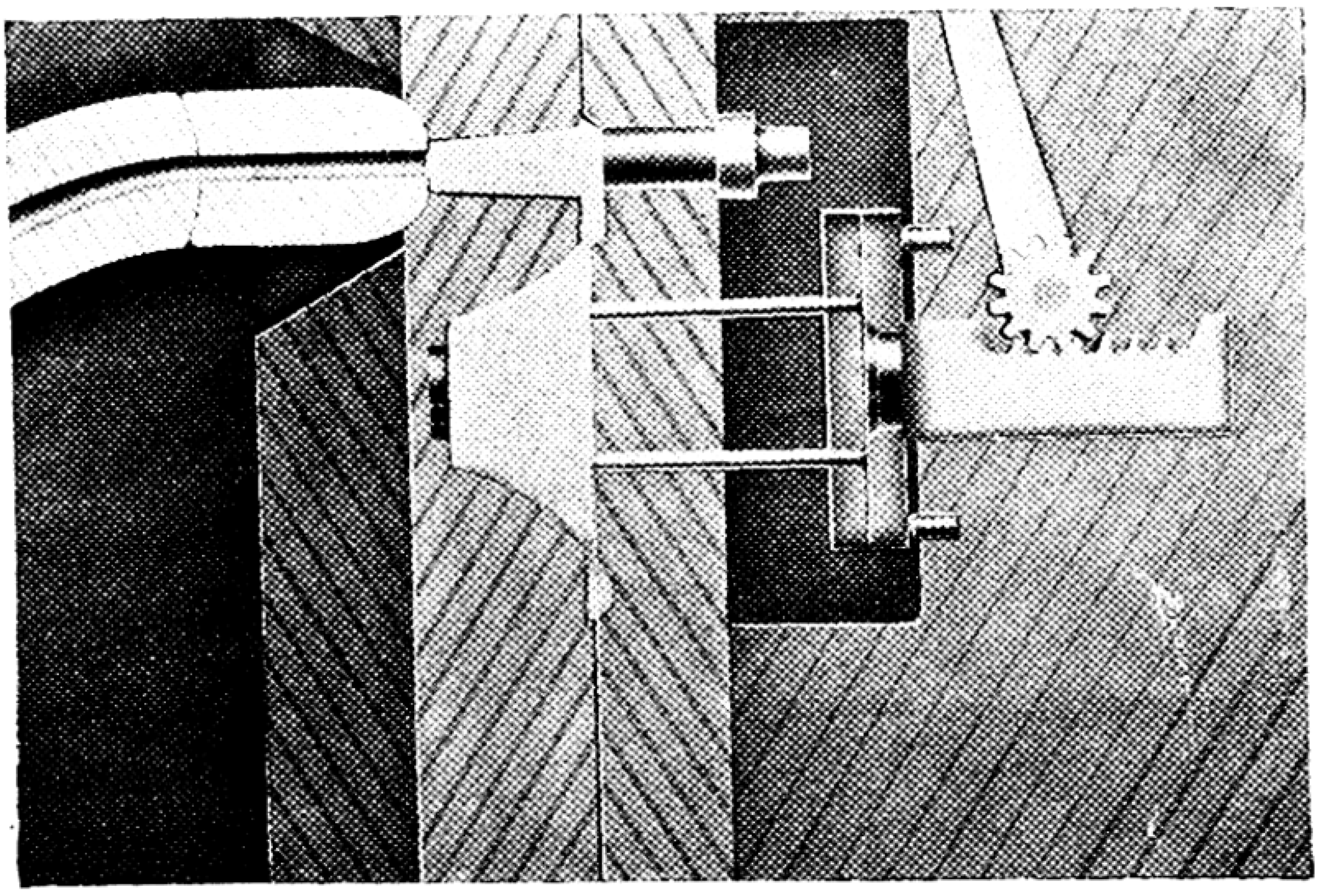


Fig. 3-7c. The cavity of the die is now completely filled. Note the metal in the overflow well at the bottom of the cavity which provides an outlet for the air entrapped in the die cavity. *Courtesy The New Jersey Zinc Company.*

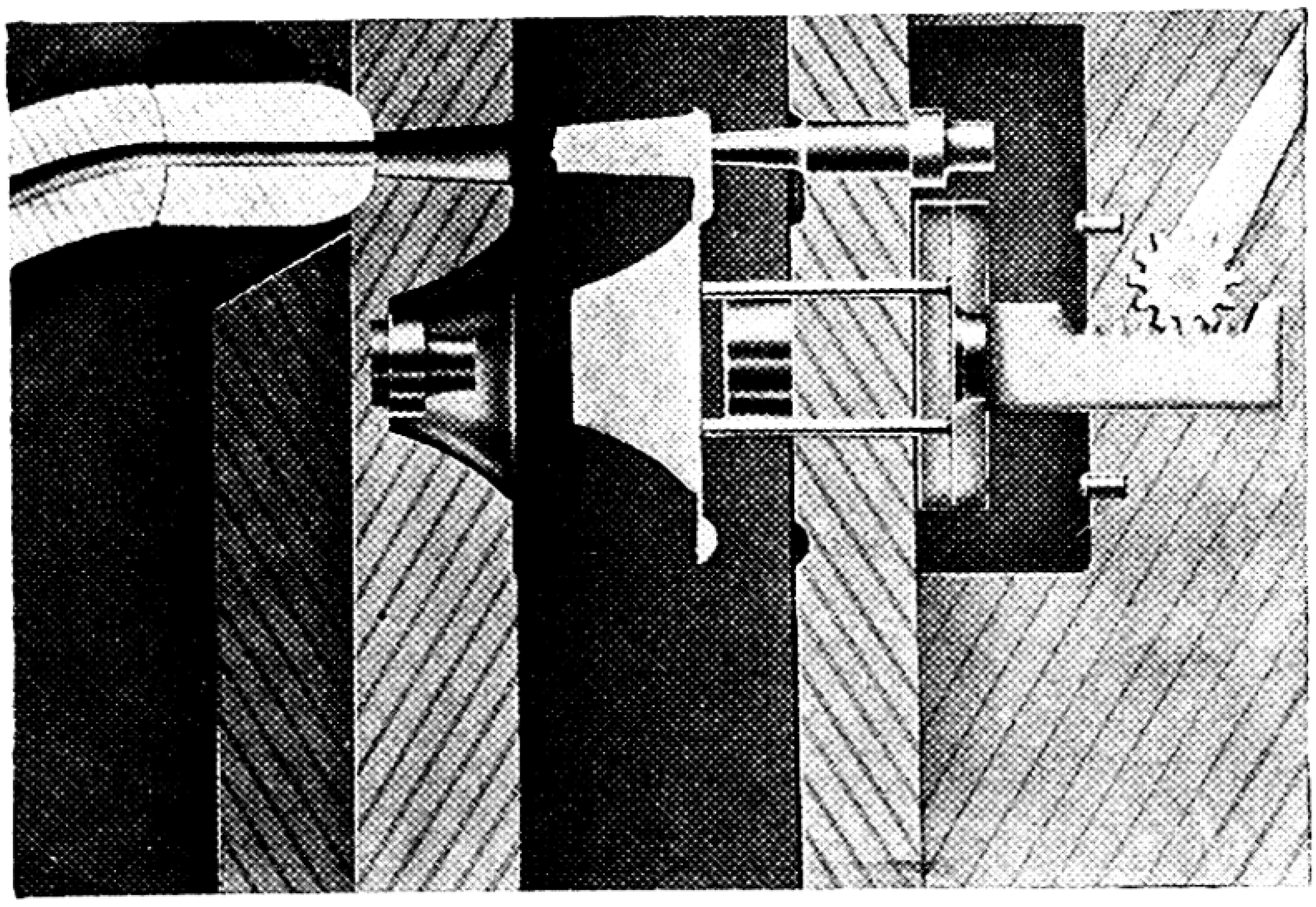


Fig. 3-7d. The die is opened to permit ejection of the casting. Note the two pins operated by a rack and pinion which free the casting from the die. *Courtesy The New Jersey Zinc Company.*

Centrifugal casting. In this process the molds are rotated at high speeds during the period of solidification. Consequently, the metal is under the pressure of centrifugal force while cooling. The molds may be lined with sand or they may be permanent in form; often sand cores are used. The molds are rotated either horizontally or vertically at speeds

Die-casting. In die-casting, the metal is forced into a permanent, machine-operated mold under pressures up to 5000 psi. The melting chamber is part of the machine. The die or mold is made in two parts; one is stationary, and the other is moved automatically by the machine.

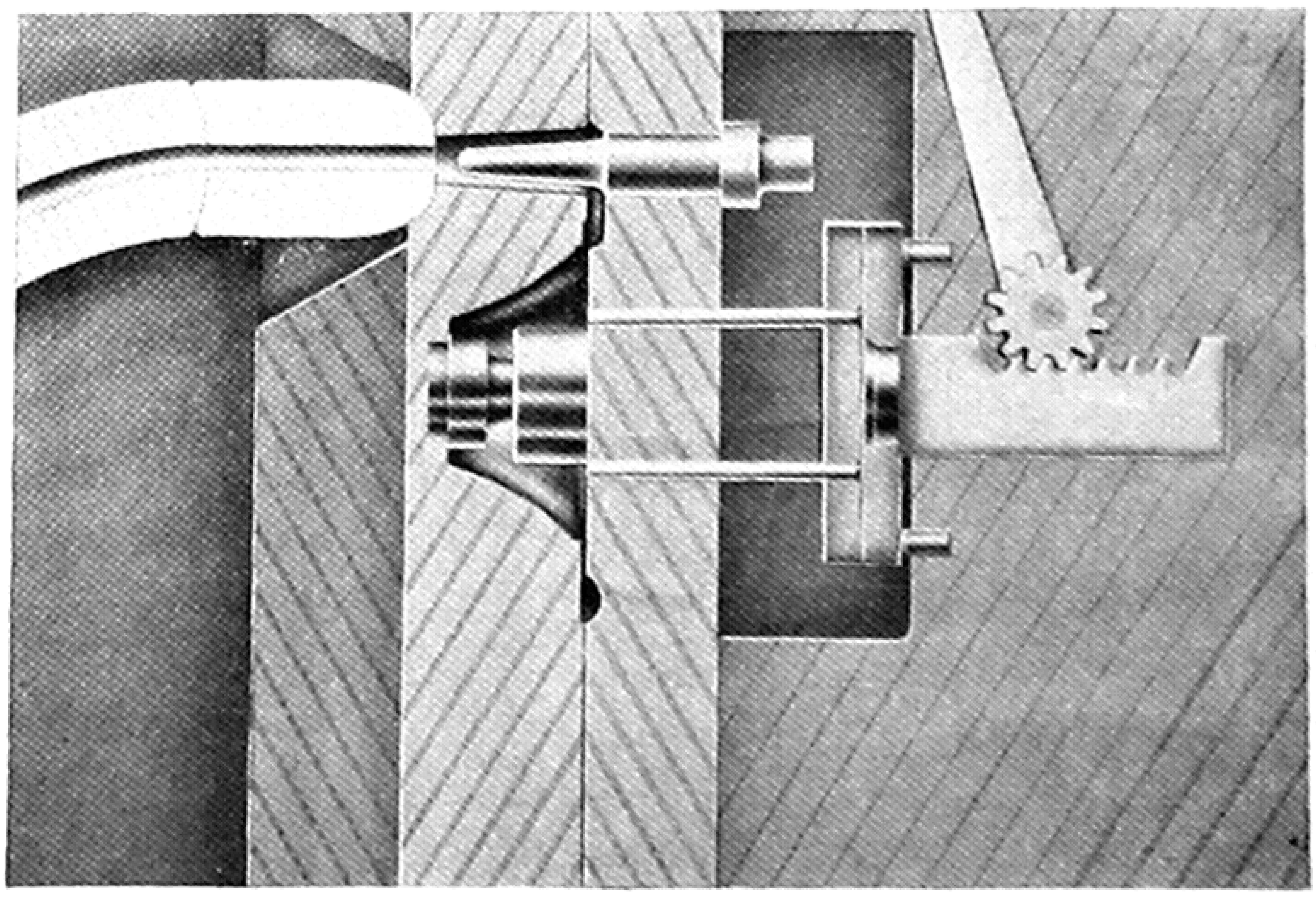


Fig. 3-7a. Here are two sections of a die closed and locked to receive from the pot the "shot" of metal to form a casting. *Courtesy The New Jersey Zinc Company.*

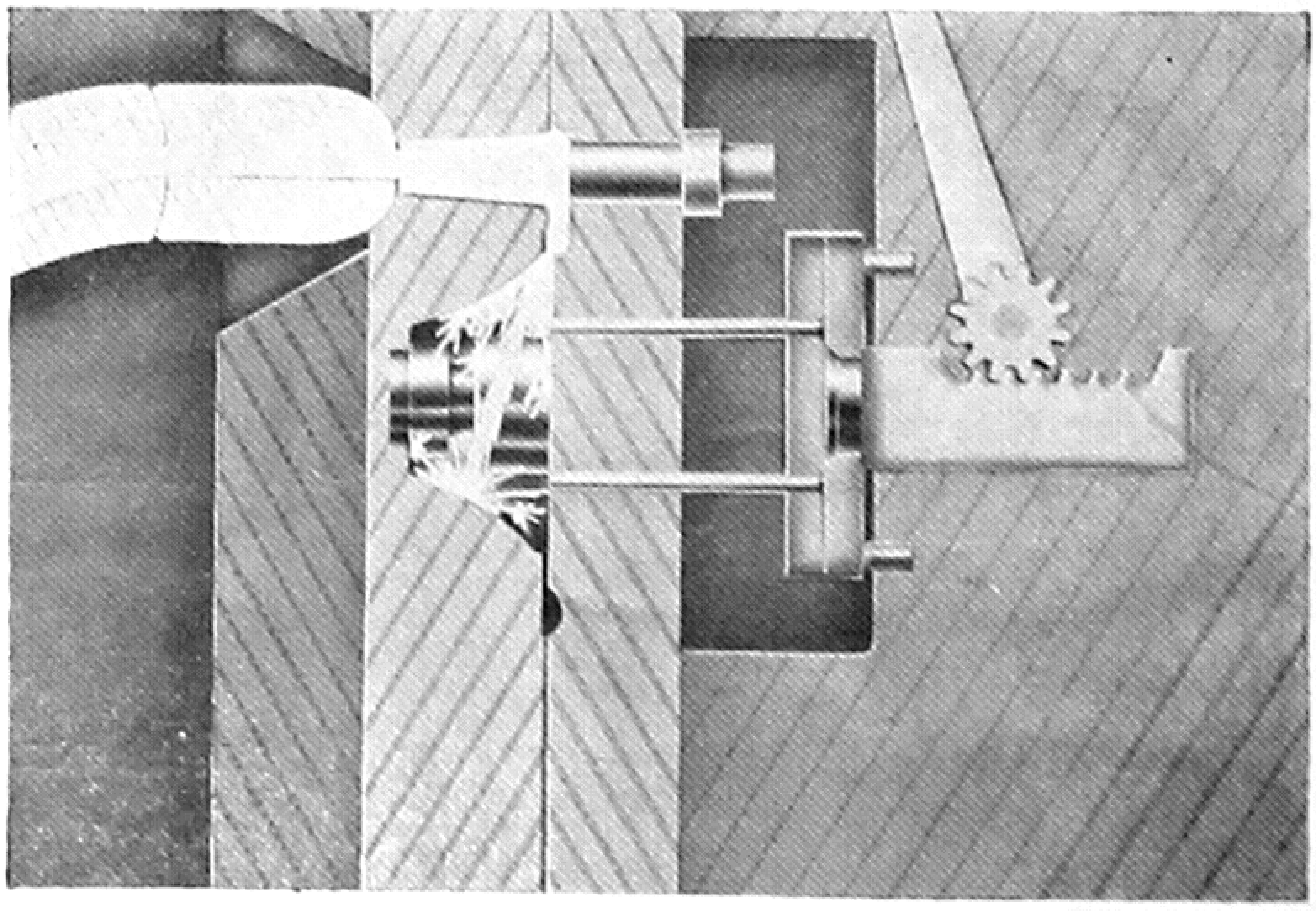


Fig. 3-7b. This drawing shows metal flowing into the cavity, which in these drawings is in the cover section of the die. *Courtesy The New Jersey Zinc Company.*

Castings are ejected from the mold by ejector pins which operate as the die opens. Aluminum and zinc alloys attack and corrode the pressure piston and cause serious trouble. *Cold-chamber casting* tends to eliminate this trouble, since the heating chamber is separated from the machine and only enough molten metal is placed in the well for one casting;

from 100 to 1200 rpm, depending upon the size and shape of the casting. The inside surface is a surface of revolution, whereas the outside surface may have flanges, lugs, or various shapes and projections. The limitation to the design is that it must be dynamically balanced. Some work has recently been done on rotation in two directions to get special shapes. The advantages of the process can be listed as:

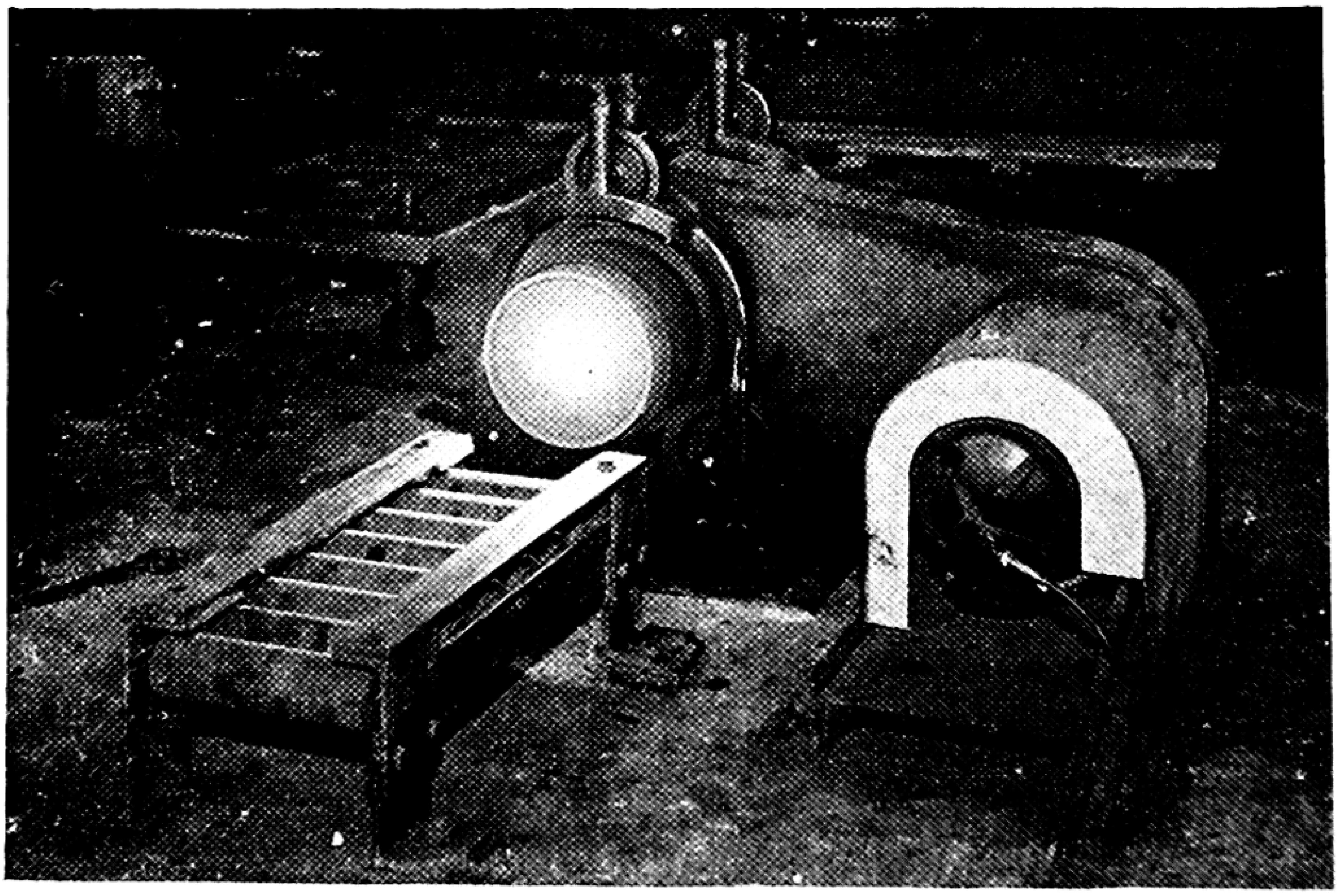


Fig. 3-8. Pouring completed, a horizontal machine spins a 33-inch tube at 700 revolutions per minute. *Courtesy Pettibone Mulliken Corporation.*

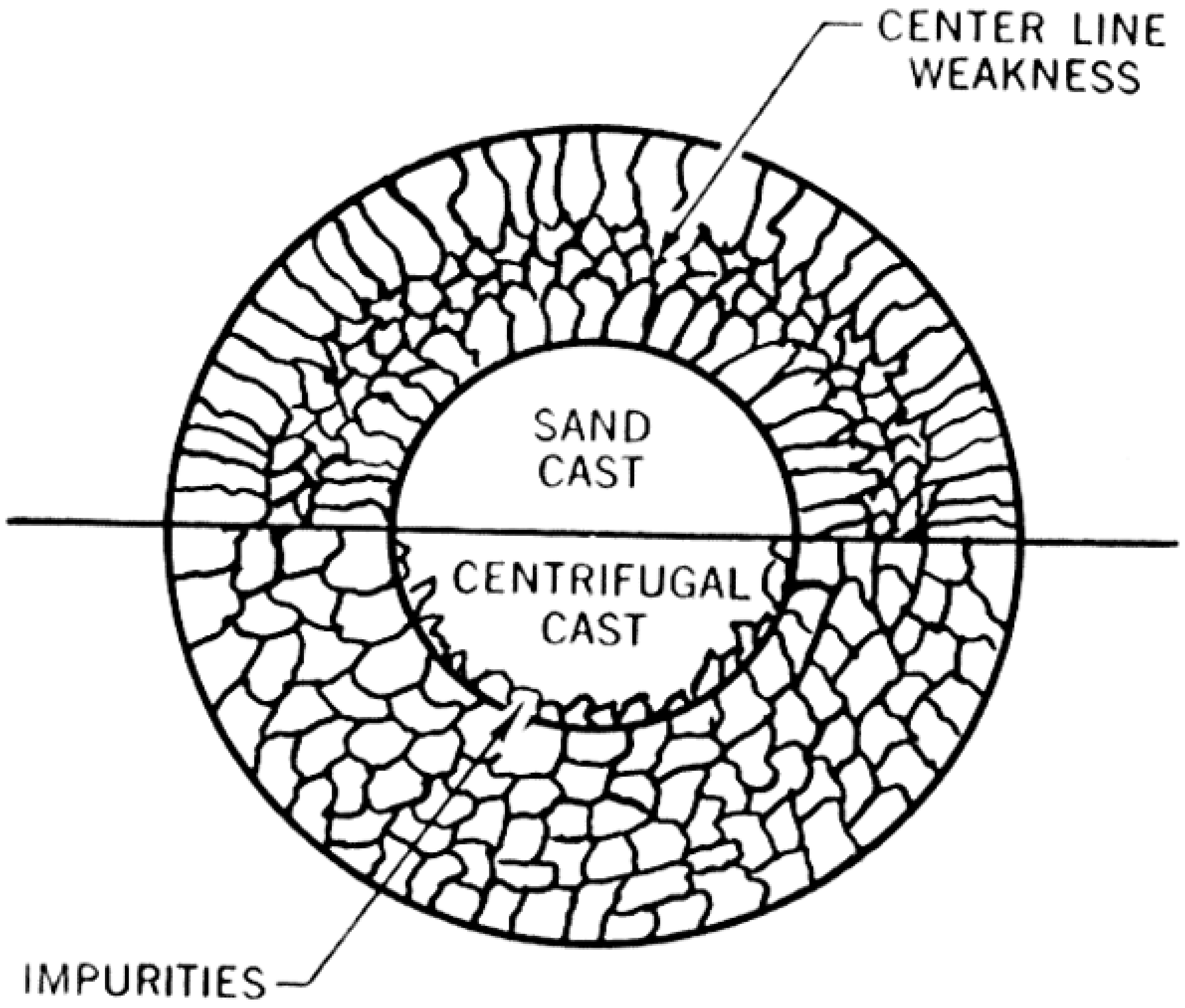


Fig. 3-9. Comparison of grain structures of sand and centrifugal castings.

(1) Cleaner, denser, and stronger casting, because the lighter dross is forced to the inside during rotation where it can be machined off.

(2) Better grain structure, as shown in Fig. 3-9.

(3) Low-cost molds.

(4) Saving of metal because of higher strength and good outside surface.

The disadvantages are:

(1) Molds must have hole from end to end.

(2) Extra metal must be provided on inside for machining.

(3) Molds be dynamically balanced.
(4) There are close tolerances on the periphery only.

The process can be used to cast such articles as gun shells, gear blanks, and pipes.

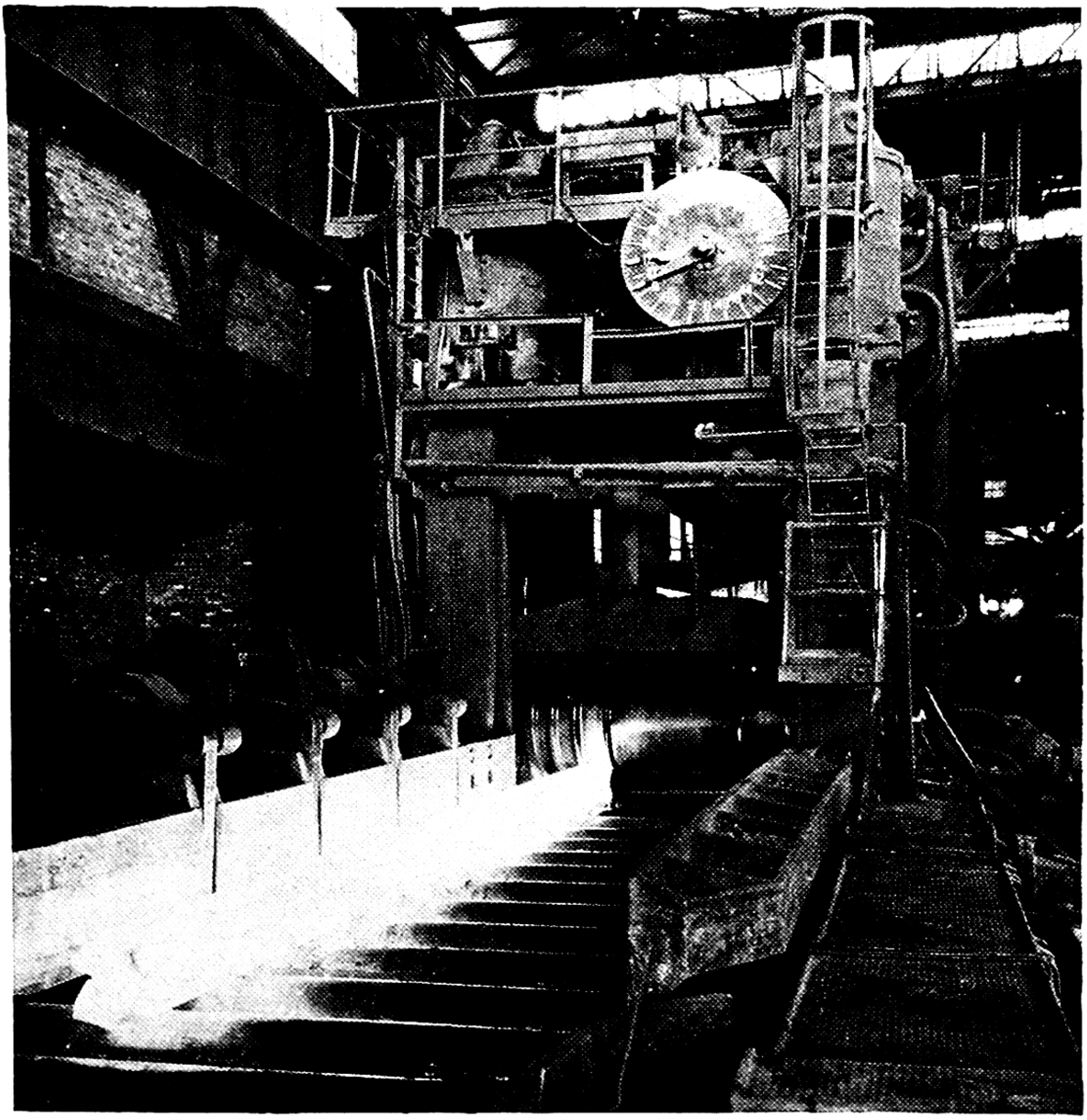


Fig. 3-10. Hot ingots are first rolled in the blooming mill until reduced to desired size. *Courtesy Bethlehem Steel Company.*

Rolling mill. In order to form an ingot into a desired shape, such as rails, structural shapes, and plates, it is hot-rolled in the rolling mill. When the ingot mold is removed, the temperature throughout the ingot varies; therefore it must be kept in a soaking pit until the temperatures are the same throughout the ingot. The soaking pit is a brick-lined

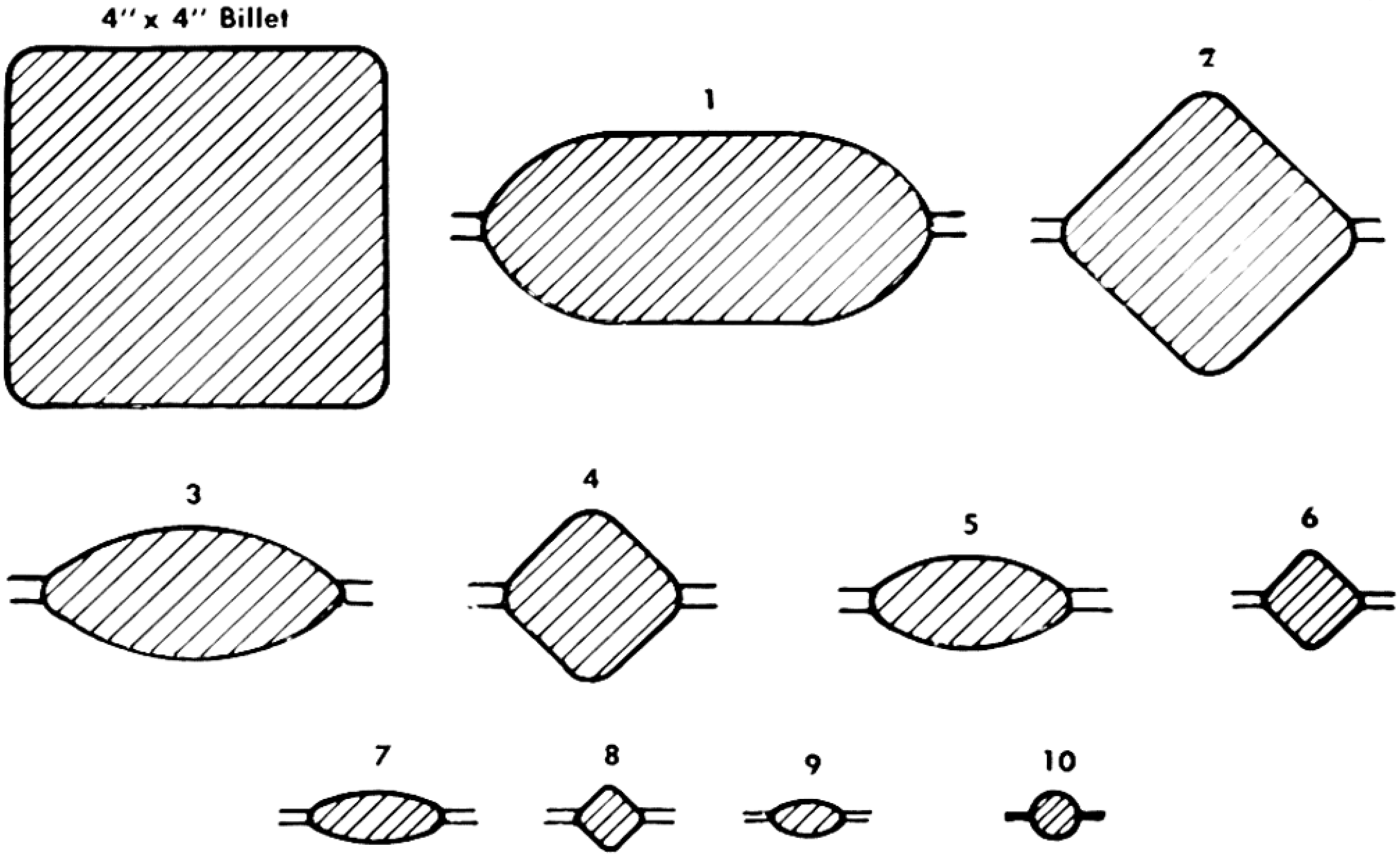


Fig. 3-11. Diagram illustrates number of passes and sequence in reducing the cross section of a four-inch by four-inch billet to round bar stock. *Courtesy Drop Forging Association.*

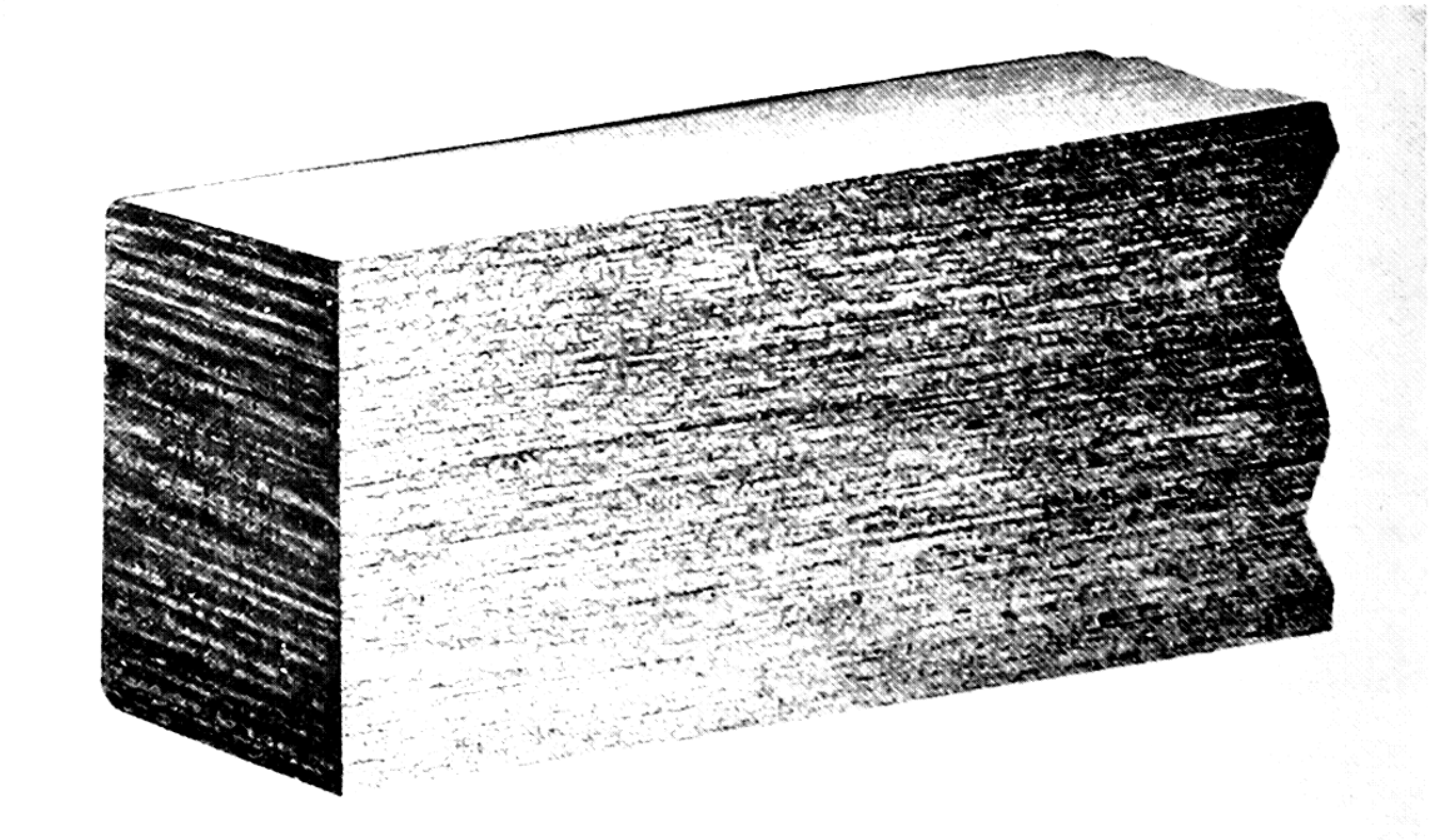


Fig. 3-12. Etched longitudinal section of billet shows refinement of grain structure and development of flow lines in the direction of the working. *Courtesy Drop Forging Association.*

pit in the ground which is heated only by the excess heat of the ingots themselves.

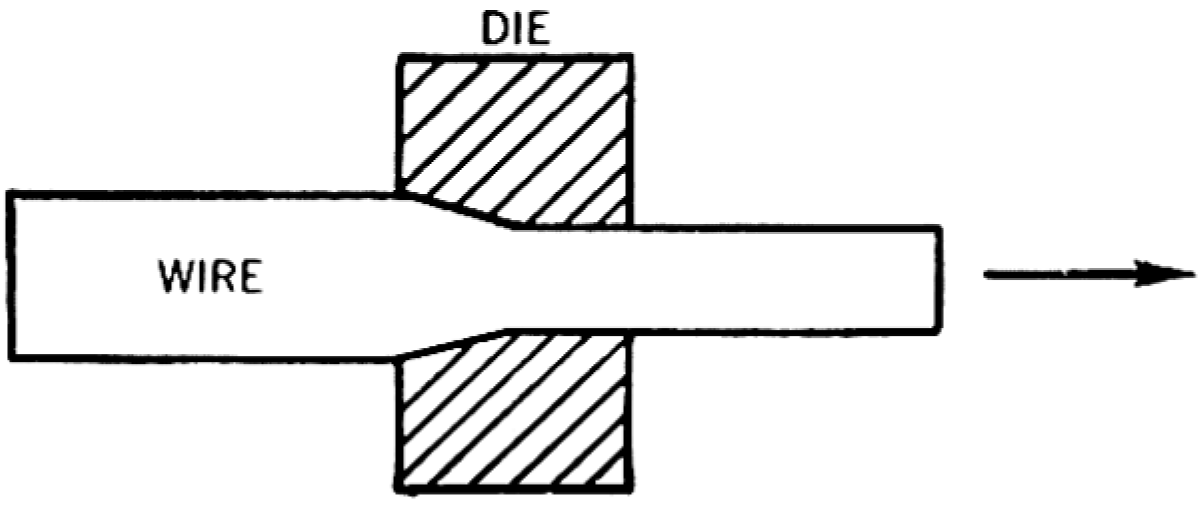


Fig. 3-13. Wire-drawing die.

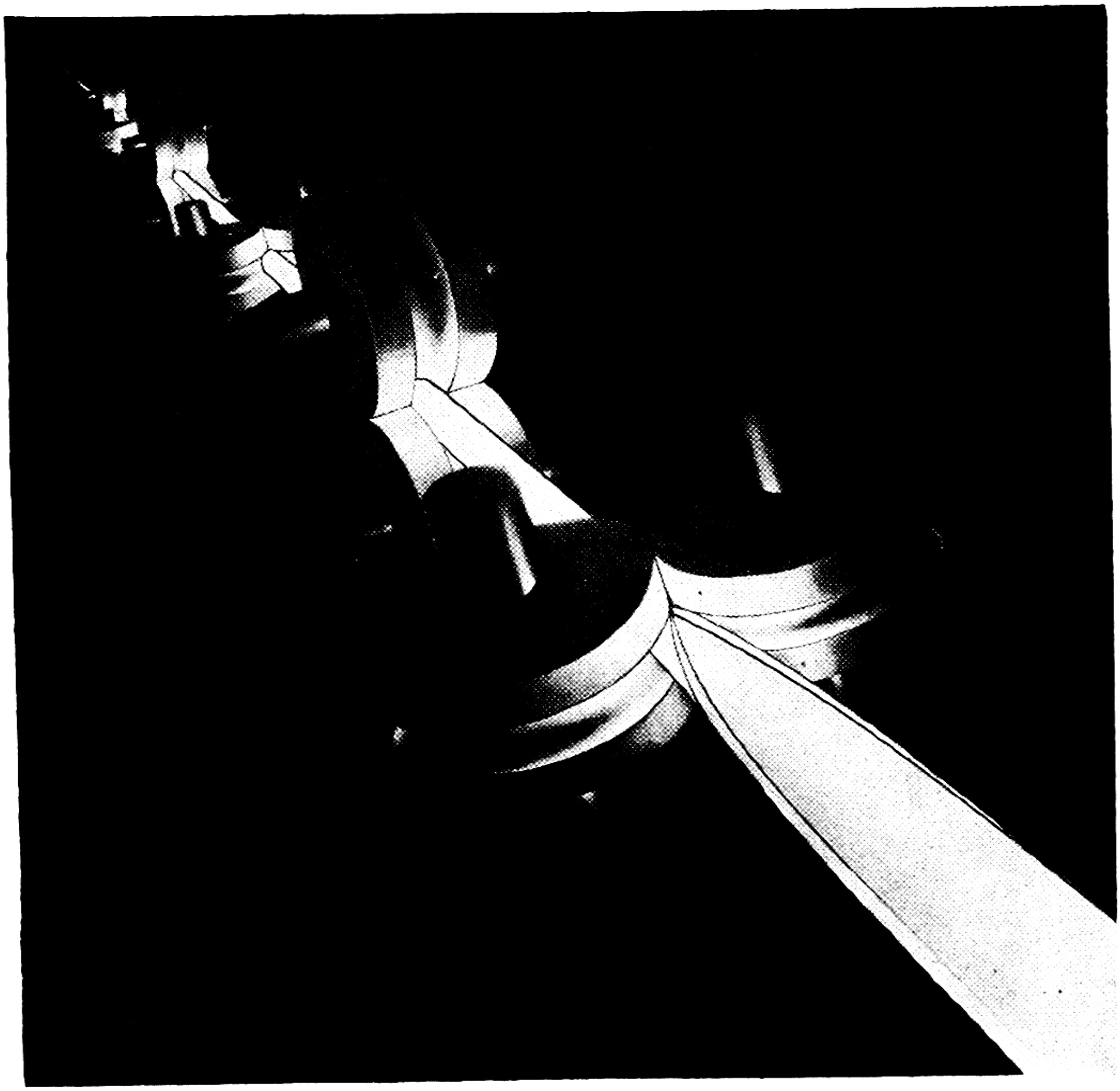


Fig. 3-14. Skelp being formed into continuous butt-weld pipe.

The actual rolling is done hot between large rolls having special-shaped flanges to give the desired form to the final product. The reduction in cross-section area for each pass averages about 10%; consequently,

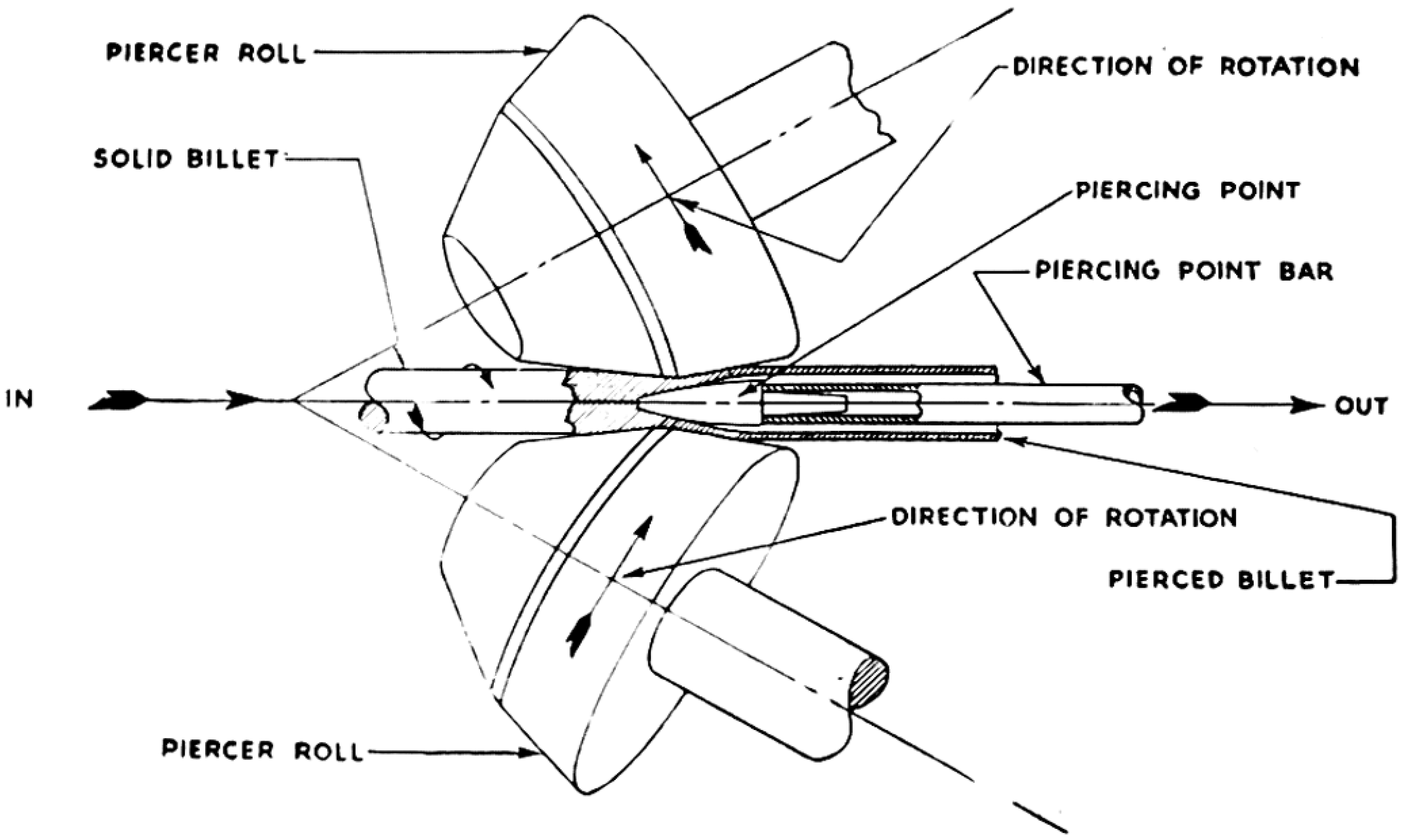
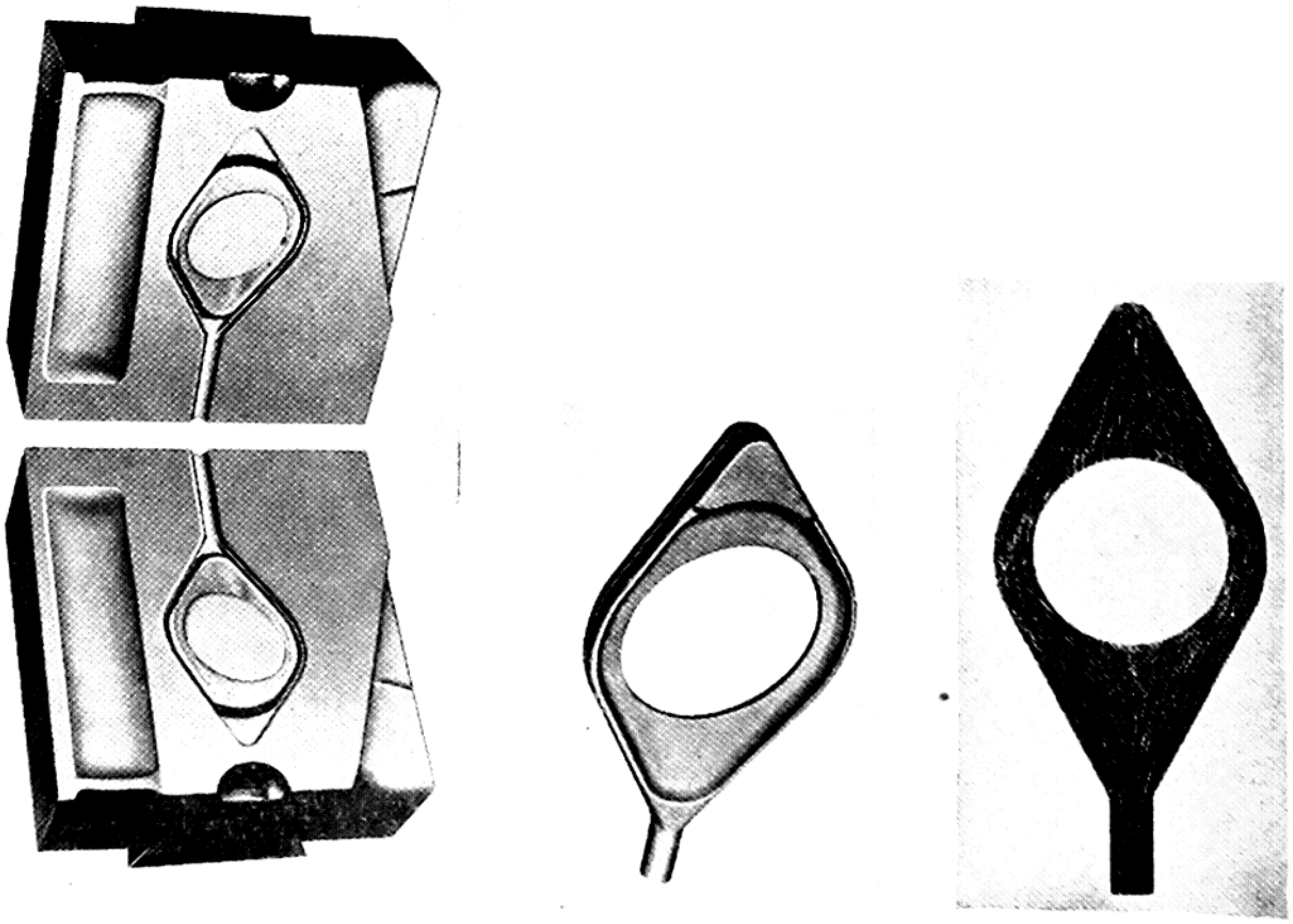


Fig. 3-15. Diagram illustrating piercing operation in making seamless tubing. *Courtesy Bethlehem Steel Company.*



(a) (b) (c)

Fig. 3-16. Flow lines in a forging. *Courtesy Drop Forging Association.*

the length increases in order to maintain a constant volume. When the length is too long to handle, the bars are cut. Figure 3-11 illustrates the steps in rolling a 4 in. × 4 in. billet (bar) to a round rod. Hot-rolled metals have a dark oxide scale and the tolerances are large. If a better surface is desired, the scale is removed and the metal is rolled cold in the last pass, making what is known as *cold-finished steel.*

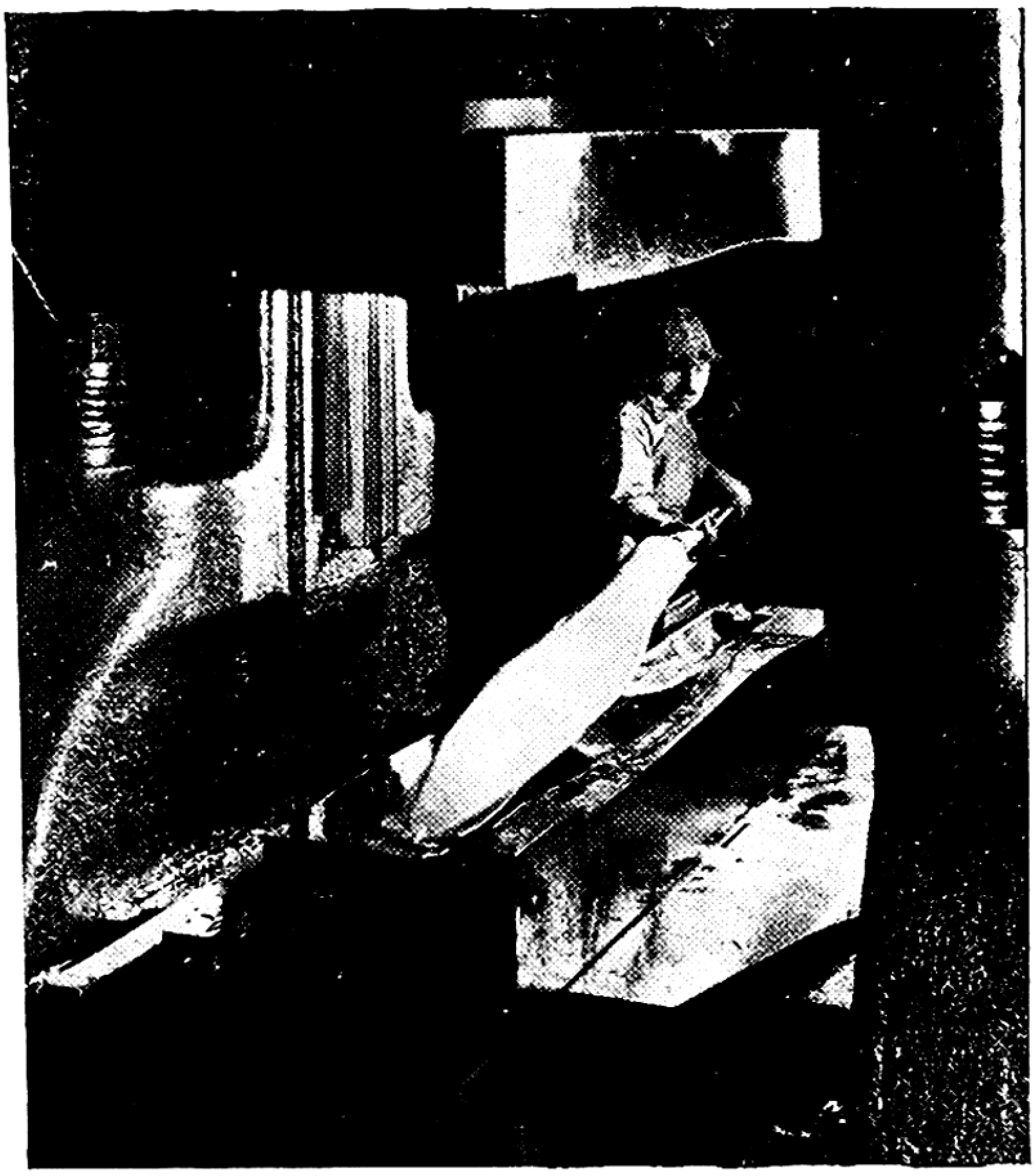


Fig. 3-17. Forging an aluminum airplane propeller. *Courtesy Aluminum Company of America.*

The rolling operation also has a beneficial effect on the grain structure of the metal. It breaks the grains into smaller parts and developes flow lines in the direction of the working, as is shown in Fig. 3-12.

If certain properties, such as hardness and strength, are wanted, the metal is rolled cold. To reduce the size of wires, they are drawn through dies, as is illustrated in Fig. 3-13. These dies are made of special steels or diamonds. The metal becomes so hard, because of work-hardening, that after every three to nine passes it must be softened. The metal is softened by heating and then is slow-cooled (annealed).

Tubing. Tubing is made either by welding or piercing. Two types of welding are used: lap welding, in which the two beveled edges of the long narrow strip, the *skelp*, are lapped over and welded; and butt welding, in which the edges meet and are pressure welded. In lap welding, the edges are first beveled, then pulled through a bell to obtain the tube. The tube is next heated to welding temperature and rolled between two rollers while a mandrel passes inside the tube between the rollers to give support for the pressure weld. In butt welding, the skelp may be drawn through a *welding bell* at welding temperature so that the seam is pressure welded, or drawn between special rolls, as shown in Fig. 3-14.

The lap weld is stronger than the butt weld, but if a still stronger pipe is necessary, a pierced seamless pipe should be used. Two special rollers (Fig. 3-15) force the white-hot billet against a mandrel which pierces the hole. The process may be repeated until the desired shape and thickness are obtained.

Extrusion. Extrusion has lately been used to make rods having special-shaped cross sections. Many parts such as brass door hinges can be completely formed except for small milling and drilling operations. This process consists of forcing metal in a plastic state through a die having a hole which will produce the desired cross section. By the proper use of extrusion, much machine-work and large amounts of scrape can be avoided.

Forging. Forging is the hammering of a metal part into the desired shape, either on an anvil or in a die, while the metal is hot. The outstanding benefit of this method is the added strength obtained by having the grain-flow lines bend around corners, as is shown in Fig. 3-16.

PROBLEMS

1. What is the main advantage of a forging?
2. What effect does hot-rolling have upon the grain structure of steel?
3. What is the difference between cold-rolled and cold-finished steel?
4. What limitations are there upon the shape of a centrifugal casting?
5. List the methods of making castings and state some pronounced advantages of each.
6. Tell which method makes the strongest tubing and why.
7. List some casting defects and tell how to avoid them.
8. List as many factors as you can which should be considered when designing a casting.
9. Why are ingots placed in a soaking pit?
10. What causes center-line weakness in castings?
11. What causes hot tears in castings and how can they be avoided?
12. What qualities should sand have in order to be a good mold sand?
13. Diagram and describe a sand mold, naming the parts.
14. Describe how a die-casting machine operates.

Chapter 4

GRAIN STRUCTURE

SINCE A metal can be fully described in terms of structure, composition, constitution, inclusion content, and grain size, it is evident that an understanding of grain structure is of primary importance in the study of metallurgy.

The atom. The atom is the fundamental material unit of an element, since it cannot be broken down further and still retain the properties of the element. An atom is made up of a nucleus, consisting of neutrons and positively charged protons, and a planetary arrangement of negatively charged electrons. The nucleus provides most of the mass of the atom; the electrons travel in orbits about the nucleus, much in the manner of the solar system. Under certain conditions, two or more atoms combine to form molecules. Each kind of molecule has specific properties, just as each kind of atom is different from all other atoms.

Atoms and molecules have different degrees of freedom of motion and position, depending upon the state of the material. In gases they can move freely in any direction, and although there is a lower limit to their spacing there is no upper limit. In liquids, they can move by each other freely, but their center distances remain nearly constant. These distances are almost the same as they would be in a solid. Since atoms and molecules have freedom of motion in a fluid, a random and changing arrangement exists.

Interacting forces between atoms and molecules determine the arrangement of the units upon solidification. If no external forces exist, the atoms and molecules will tend to arrange themselves in an orderly fashion so that all the forces are in equilibrium. This orderly structure, the arrangement of which depends largely upon the kind of material and its temperature, has specific geometrical shapes consisting of plane surfaces which are at characteristic angles with each other. These shapes are called *crystals*.

The plane surfaces are planes in which the atoms have arranged themselves, and they are parallel to the other planes in the crystal from the center outward. The arrangement of atoms is called the *space-lattice.* Figure 4-1 shows a simple cubic lattice in which each atom is represented by a dot. The arrangement about each atom is the same, except on the surface, where the spacing may differ in order to equilibrate the forces. Three planes pass through each atom at right angles to each other. Other polyhedral forms of crystals make different space-lattices.

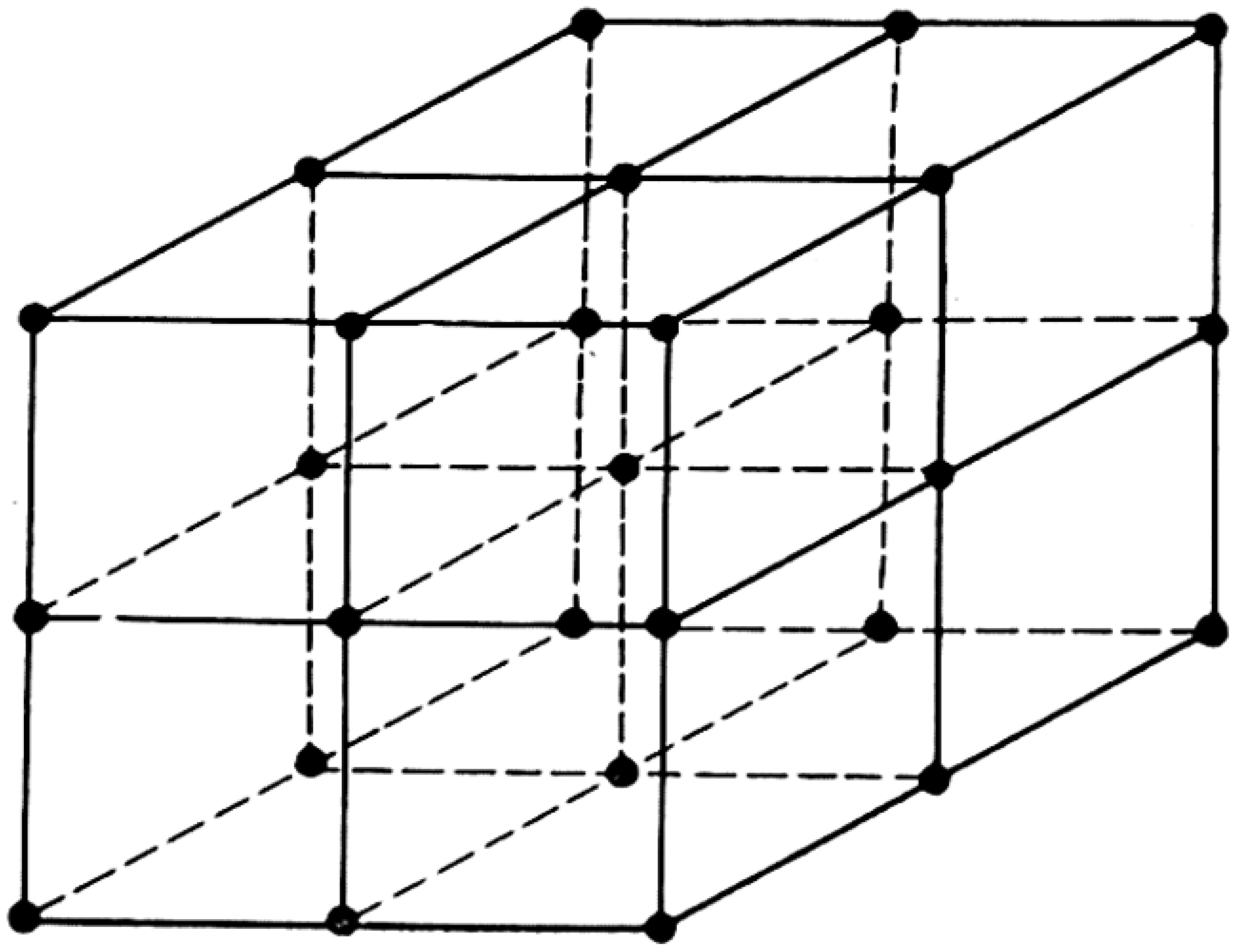


Fig. 4-1. Arrangement of atoms of cubic space-lattice.

Crystal growth. The surface atoms of a crystal have energy available for attracting free atoms into the lattice, thus causing the crystal to grow by adding planes parallel to existing surface boundaries. The important sources of free atoms or molecules from a metallurgical point of view are liquid metals and, under certain conditions, solids. The atoms in a solid may have some freedom of motion at certain temperatures.

If two different materials crystallize side by side, and if each crystal retains the properties of one of the ingredient materials, the materials are *insoluble* in each other. If, on the other hand, the materials mix and form crystals which are different from the original materials, they are said to be *soluble* in each other. Metals may be completely insoluble, partially soluble, or completely soluble, depending upon the kinds of metals, the proportions in the alloy, and the temperature.

Metals may be soluble in the solid as well as in the liquid state. If the atoms of two metals combine to form the crystal lattice of one of them, they are said to be in *solid solution.* There are two kinds of solid solutions: the *substitution* class, where some atoms of the solute replace some of the atoms in the solvent lattice; and the *interstitial* class, where atoms of the solute are interspersed in the open spaces between the atoms of the solvent.

Solidification of metals. For some unexplained reason, as a molten metal cools, certain atoms will arrange themselves into tiny crystals which serve as nuclei for larger crystals. The nuclei form at the freezing temperature, usually at the mold surface where the rough mold provides points of excess surface energy which promotes changes, and where the temperature is lowest. As the crystals form, the atoms give off heat energy, which tends to maintain the metal at one temperature until all the metal has frozen. Figure 4-2 illustrates the constant temperature during freezing.

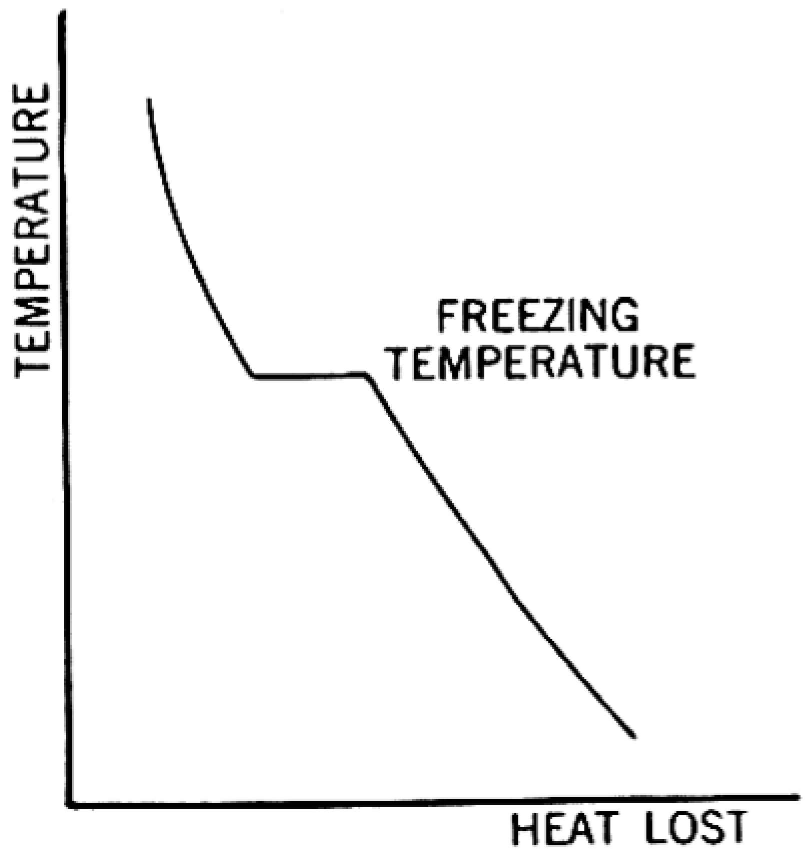


Fig. 4-2. Cooling curve showing freezing point.

If the liquid is cooled very fast, there is little time for crystal growth. Therefore a large number of nuclei form to create small crystals or *grains*. On the other hand, slow cooling allows time for crystal growth, so the metal solidifies in large crystals before many nuclei have formed. Cooling metal from a high temperature has the same effect as slow cooling, since the interior of the mass provides heat to maintain the temperature at the surface of the casting where the first crystals form.

Crystals grow out from their faces by adding layers of atoms, but the rate of growth from the various faces differs. This variation makes the enlarged shape of the crystal different from that of the nucleus. The crystals of a metal often take on the appearance of pine trees as they grow: thus the name *dendrites*.

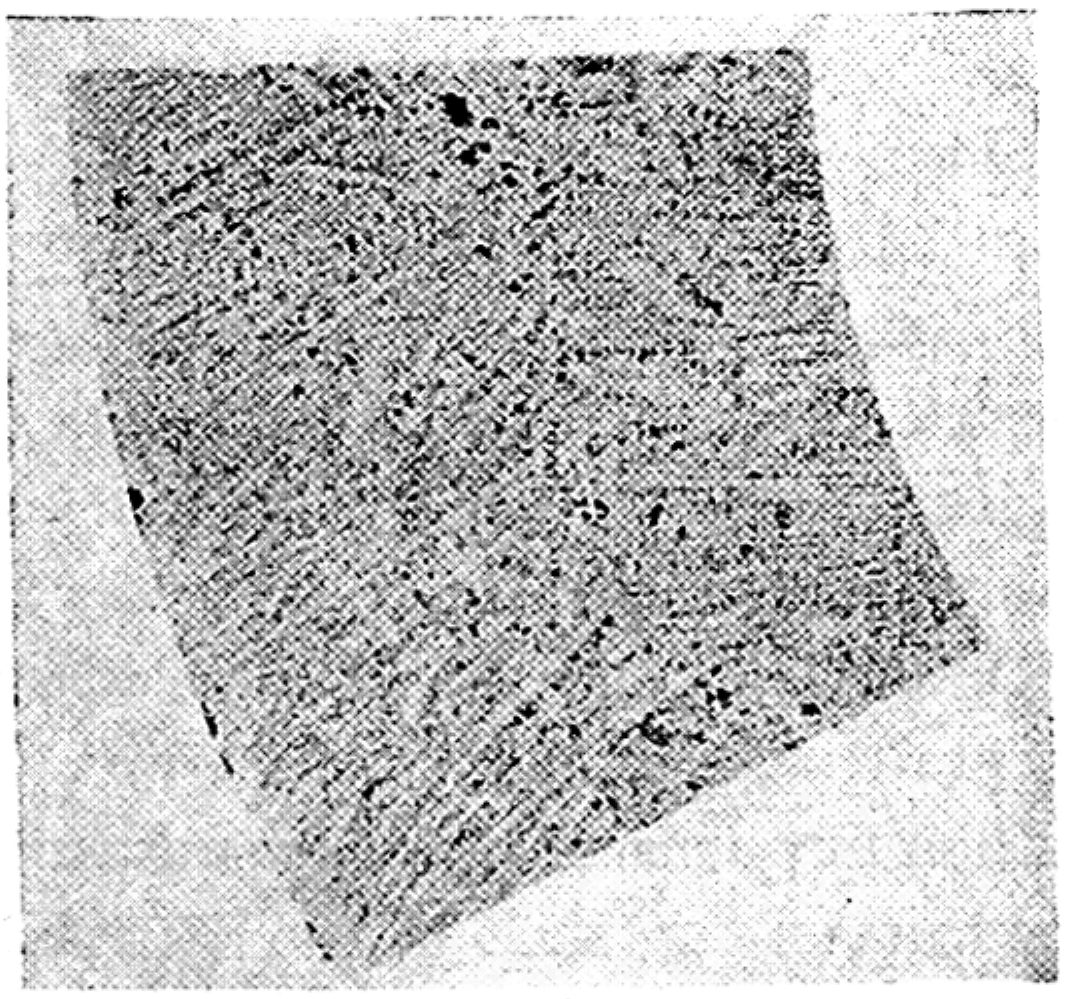


Fig. 4-3a. Macro-etch of dendrites. *Courtesy Pettibone Mulliken Corporation.*

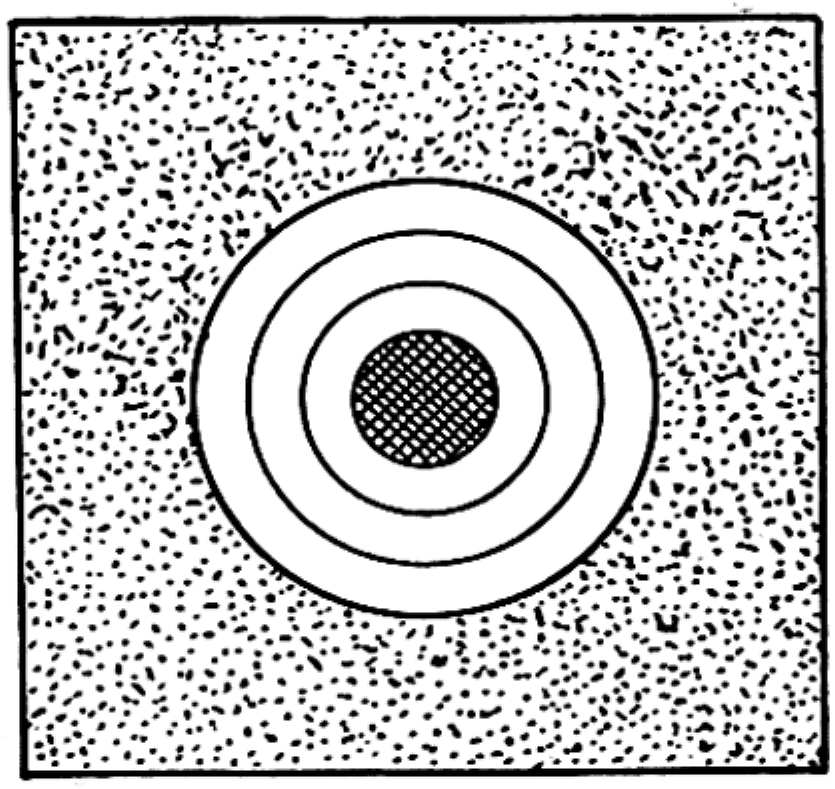


Fig. 4-3b. Grain formation in sand mold.

The crystals in a mold start to form at the surface first and then grow inward. Since large numbers of nuclei form at the same time, there is no room for growth except inward. Therefore the crystals are long and *columnar*. Figure 4-3b shows a round mold. The outside surface solidified first, then successive layers of metal were added as the inside molten metal cooled. Since the volume of most metals shrinks as the fluid cools and freezes, a shrinkage cavity develops in the center, as is illustrated by the cross-hatch. The volume increases slightly as the metal solidifies, but the increase is small compared to the shrinkage that occurs during an appreciable temperature change.

When small, foreign, solid particles are mixed in the liquid, they tend to become the center of crystals. Thus grain formation is promoted at isolated points in the interior of the liquid.

Effect of grain structure on strength. Consider that two crystal nuclei have formed with orientations as shown at "start" in Fig. 4-4, where the dots represent atoms and the lines the atom planes. If only one grain were growing, the atoms would arrange themselves in parallel planes until all the liquid solidified as one large crystal. However, the second grain is growing toward the first, thereby preventing a continued orderly arrangement. The atoms at the boundary are in a *strained* condition; that is, they have been forced out of their natural positions. These natural positions are the positions of equilibrium where the attractive gravitational forces and the repulsive electrical forces of the positive atomic nuclei are balanced. Within certain limits, the farther an atom is pushed out of its natural position, the greater the force necessary to push or strain it. According to the definitions of strength and hardness, this concept would indicate that grain boundaries, when cold, would be the hardest and strongest part of a grain: the greater the strain, the greater the strength and hardness. When impurities which are unwanted by the growing crystal are present, they may be pushed to the boundary. Here they may have either a strengthening or a weakening effect, depending upon the material. This strained-space-lattice theory can be employed to explain all types of hardening processes.

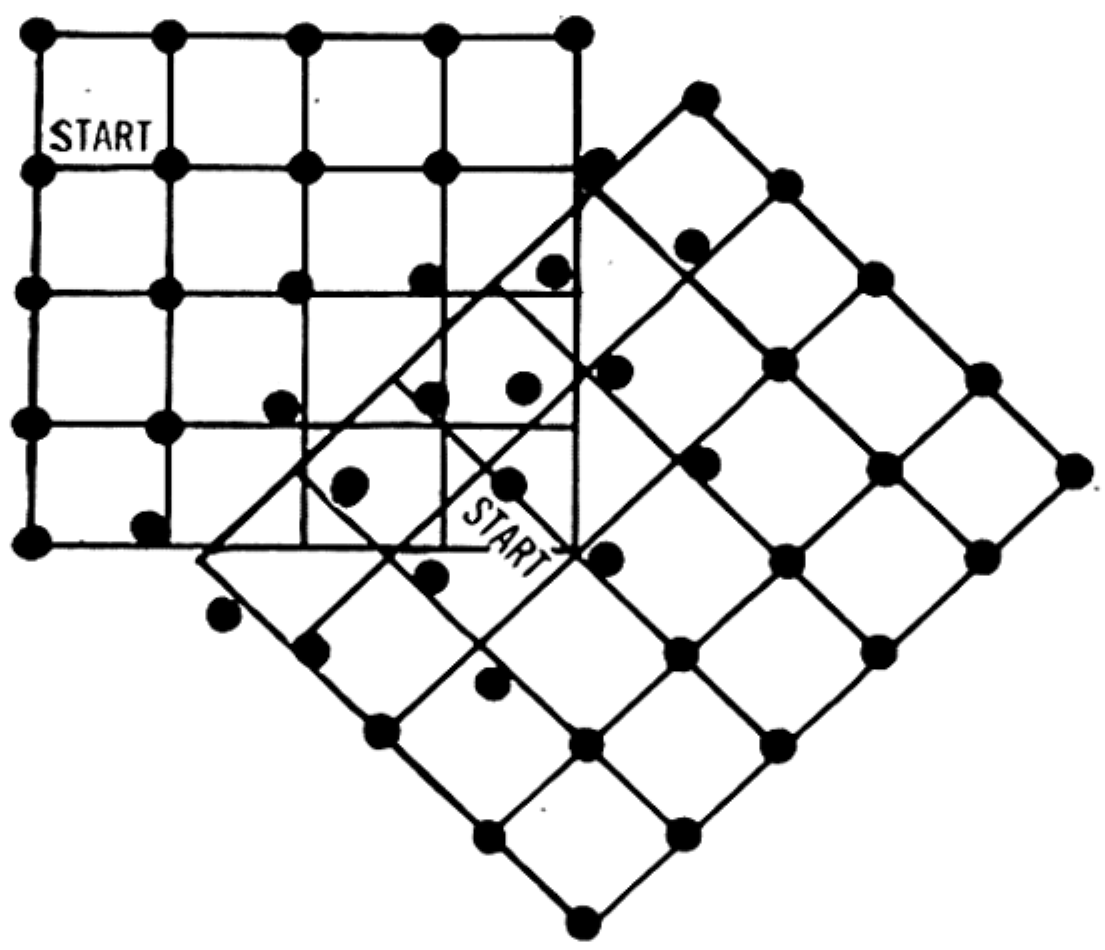


Fig. 4-4. Boundary strain due to orientation of grains.

Grain size. By using the above theory, it is possible to predict to some extent certain properties of a material. Except at elevated temperatures where boundary atoms have some freedom of action, the smaller the grain the more boundary, and therefore the stronger and harder the material.

The properties of low-alloy steels show a marked response to a change in grain size. Fine-grained steels have a greater toughness and resistance to impact. Their heat-treating temperatures are less critical and they have a smaller tendency to warp and crack. They are easier to cold-draw, to form, and to roll. Many fine-grained stainless steels are less susceptible to intergranular corrosive action.

Large-grained steels have a higher creep strength, and are deeper-hardening, but have a lower fatigue strength. Their magnetic properties are better than fine-grained steels.

Effect of grain orientation. The magnetic and electrical properties differ in a grain according to the direction in which the properties were measured. The electrical resistance is less along an edge than along any diagonal, and magnetic saturation is reached with fewer ampere-turns along the edge than along a diagonal. The fact that these properties are the same in any direction in an ordinary piece of metal indicates that the grains are placed at random. By special processing, the grains may be aligned to obtain the desired properties, as pictured in Fig. 4-5.

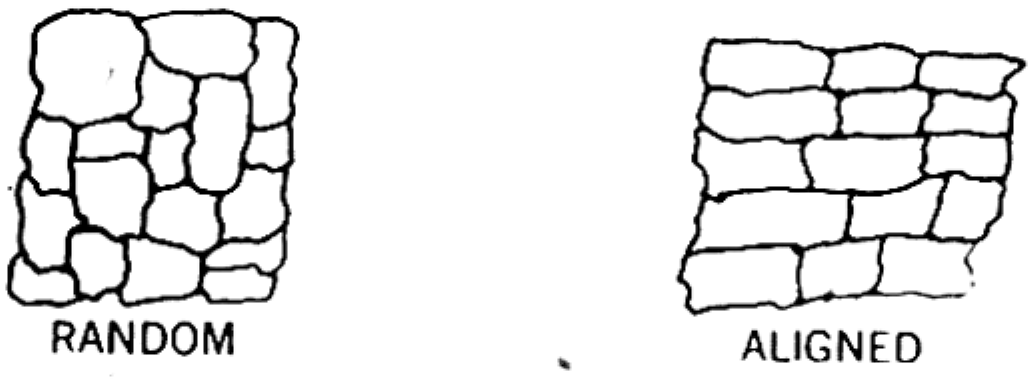


Fig. 4-5. Random and aligned grain structure.

Work-hardening. When a metal is hardened by deformation while cold, it is said to be *work-hardened*. The hardening effect may be explained by considering that each plane of atoms in a grain is represented by a card in a deck of playing cards. If the cards are pushed, their surfaces slide by each other easily, as shown in Fig. 4-6a; on the other hand, it is difficult to deform the deck by tearing the cards. Should the pushing be continued, the cards might become two separate groups, as in Fig. 4-6b, thus representing two smaller grains. The planes where slip is easy are called *slip-planes*. It can now be understood why a grain hardens when it is deformed. The slipping causes a disarrangement of the atoms within the grain, thereby requiring a greater force to further strain the space-lattice, and it also increases the boundary by flattening the grain and by breaking some of the grains. Many products requiring strength or hardness are left in the work-hardened condition caused by the forming process, such as copper wire to be strung over long spans, and piano wire, which needs a high elastic limit.

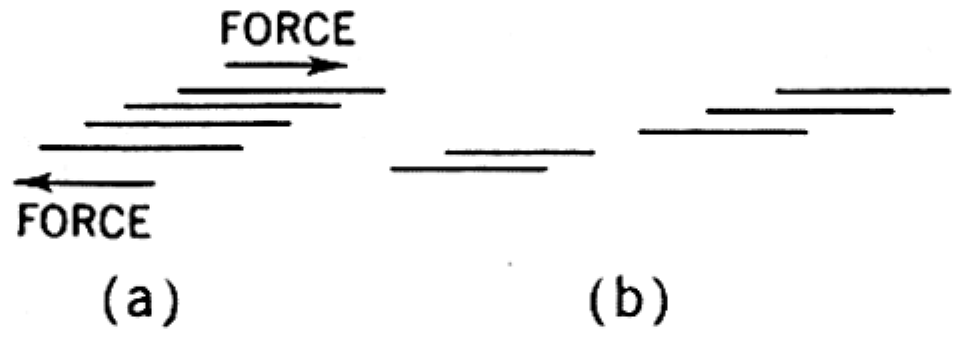


Fig. 4-6. (a) Strained grain showing slip planes. (b) Broken grain.

One effect of shot-peening (peening by hurling shot onto the surface) is to harden and strengthen the surface of a material, thus helping to prevent fractures which start at the surface.

Precipitation-hardening. Many materials, such as beryllium-copper, duralumin, and steels containing oxides, tend to harden at room temperature over periods up to several days. These metals contain submicroscopic particles of material which are more soluble in the metal at high temperatures than at low temperatures. When the metal is cooled, they are caught within the crystals, forming a supersaturated solution, and since they are not so soluble at the lower temperatures, they work their ways to the boundary. In the process of going to the boundary, the particles upset the space-lattice and cause strain or work-hardening. A second effect that occurs is that the particle acts as an abrasive between the boundaries, making motion between the grains more difficult. This is sometimes called *age-hardening* or *aging*.

Temperature effects. A perfectly elastic material will be deformed a certain amount when a load is applied and will maintain that deformation until the load is removed. It will then return to its original shape. Many metals which are perfectly elastic at low temperatures tend to change shape slowly under a given load and to take on a permanent strain at elevated temperatures. The slow deformation is called *creep.* Creep becomes a very important factor in such high-temperature equipment as jet engines and high-pressure steam turbines. Many metals become extremely brittle at low temperatures. This fact is of extreme importance in the design of equipment to be used in very cold climates.

SUMMARY AND DEFINITIONS

Crystal. The word crystal is used to describe a piece of matter throughout which the atomic arrangement is natural and regular. In a more specific sense, it is used to describe the exact shape of a crystal that has formed under complete freedom.

Grain. A grain is one crystal.

Space-lattice. The term space-lattice indicates the arrangement and spacing of the atoms in a crystal.

Solubility. When two metals crystallize side by side and each crystal retains the properties of either one of the metals, they are said to be *insoluble.* If the crystals formed have the properties of none of the ingredient materials, they are *soluble.*

Solid solution. A group of atoms of more than one metal which form into the space-lattice of one of the metals.

Work-hardening. Also called *strain-hardening.* The increase in hardness due to inelastic deformation below the recrystallization temperature.

Precipitation-hardening. This type of hardening is caused by the travel at lowered temperatures of particles of insoluble, supersaturated material from the inside of a crystal to the boundary, thereby straining the space-lattice. It occurs in materials which are more soluble at high temperatures than at low temperatures.

Creep. Creep is the slow inelastic deformation of a metal at elevated temperatures under stress.

The strained space-lattice theory of hardening. Based upon the theory that any displacement of atoms in a crystal causes the requirement of a greater force to further displace the atom.

PROBLEMS

1. What is a crystal?
2. What is a grain?
3. What is meant by a space-lattice?
4. Why is a small-grained material at room temperatures usually stronger than a large-grained material?
5. Describe how crystals form in a cooling casting. Why do shrinkage cavities occur?
6. How can the strained-space-lattice theory be used to explain work-hardening?
7. Describe the process of precipitation-hardening.
8. What is creep and why is it an important consideration?
9. How are crystals formed?
10. What effect may small impurities have upon grain formation?
11. What happens to atoms when they freeze?
12. What is a solid solution?
13. When do slip-planes occur in the space-lattice?
14. Describe the difference in the crystalline arrangement of a mixture of soluble and a mixture of insoluble metals.
15. What effects does grain size have upon the properties of steel?

Chapter 5

THE EQUILIBRIUM DIAGRAM

THE EQUILIBRIUM, or constitution, diagram is a great aid in the study and use of alloys. It can help to predict properties, indicate heat-treating temperatures, aid in choosing a type of heat-treatment, and show the proper percentages of the alloying elements. It is a diagram which shows the temperatures of critical changes at varying percentages of the alloying metals.

Cooling curve. When a pure metal is heated above the melting point and allowed to cool, a curve such as that in Fig. 5-1 can be plotted. The data for the curve can be secured by taking the temperature of the metal at frequent intervals of time. These data are then plotted with the temperature as the ordinate and the time as the abscissa. The slope of the upper part of the curve is steep. As the metal cools, the slope becomes more gradual, because the cooling rate is proportional to the temperature difference between the metal and its surroundings.

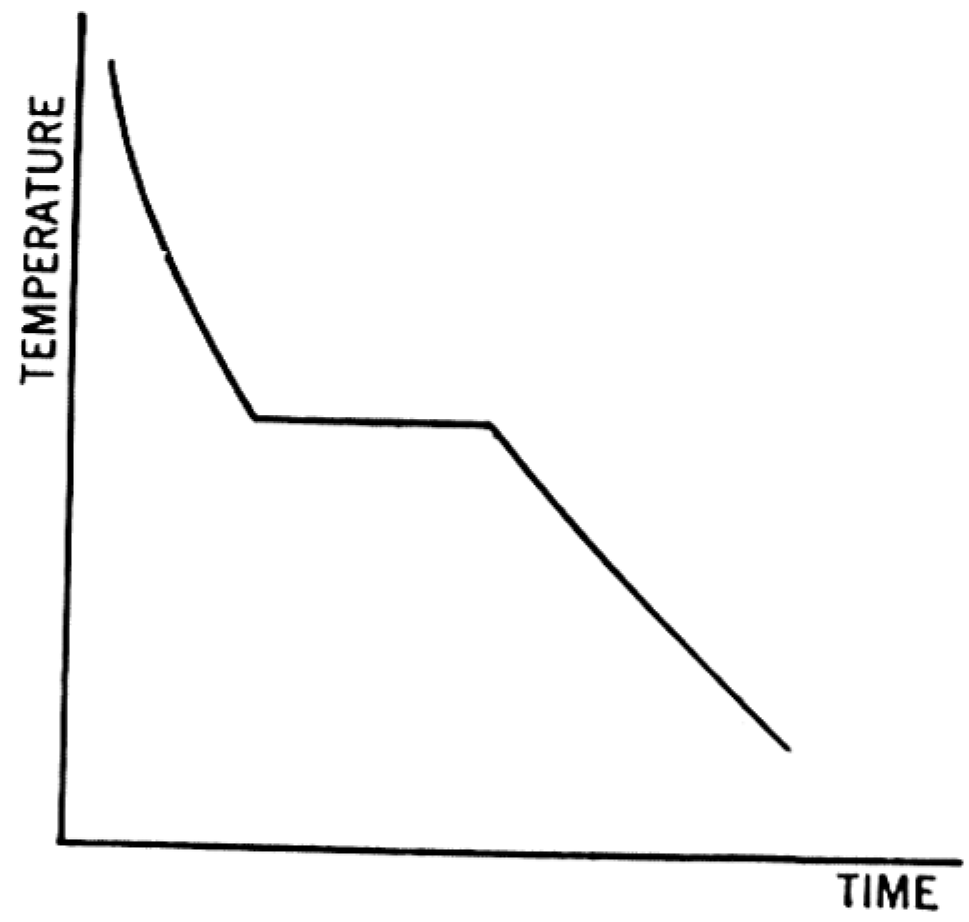


Fig. 5-1. Cooling curve showing constant temperature transformation point.

A study of the curve shows that a point exists at which the temperature is constant for a period of time. This is the temperature at which "freezing" or solidification occurs. It was pointed out in Chapter 4 that during crystallization atoms give off heat energy which tends to maintain a constant temperature until all the material is solid. It is this freezing period that shows up as a constant temperature line in Fig. 5-1. Above the freezing point, the metal is all liquid; at the freezing point, the metal is a mixture varying from 100% liquid to 100% solid; and as soon as the metal is 100% solid, the temperature again begins to drop at an ever-decreasing rate. Whenever crystalline changes occur in the structure of a metal, an absorbing or giving up of heat energy takes place, which shows up as a constant temperature line on the temperature-energy curve.

Equilibrium diagram construction. Consider the set of cooling curves shown in Fig. 5-2. This series of curves is for varying percentages of a two-metal alloy, called a *binary alloy*. Study will indicate that a certain regularity exists in the variation of the critical temperatures.

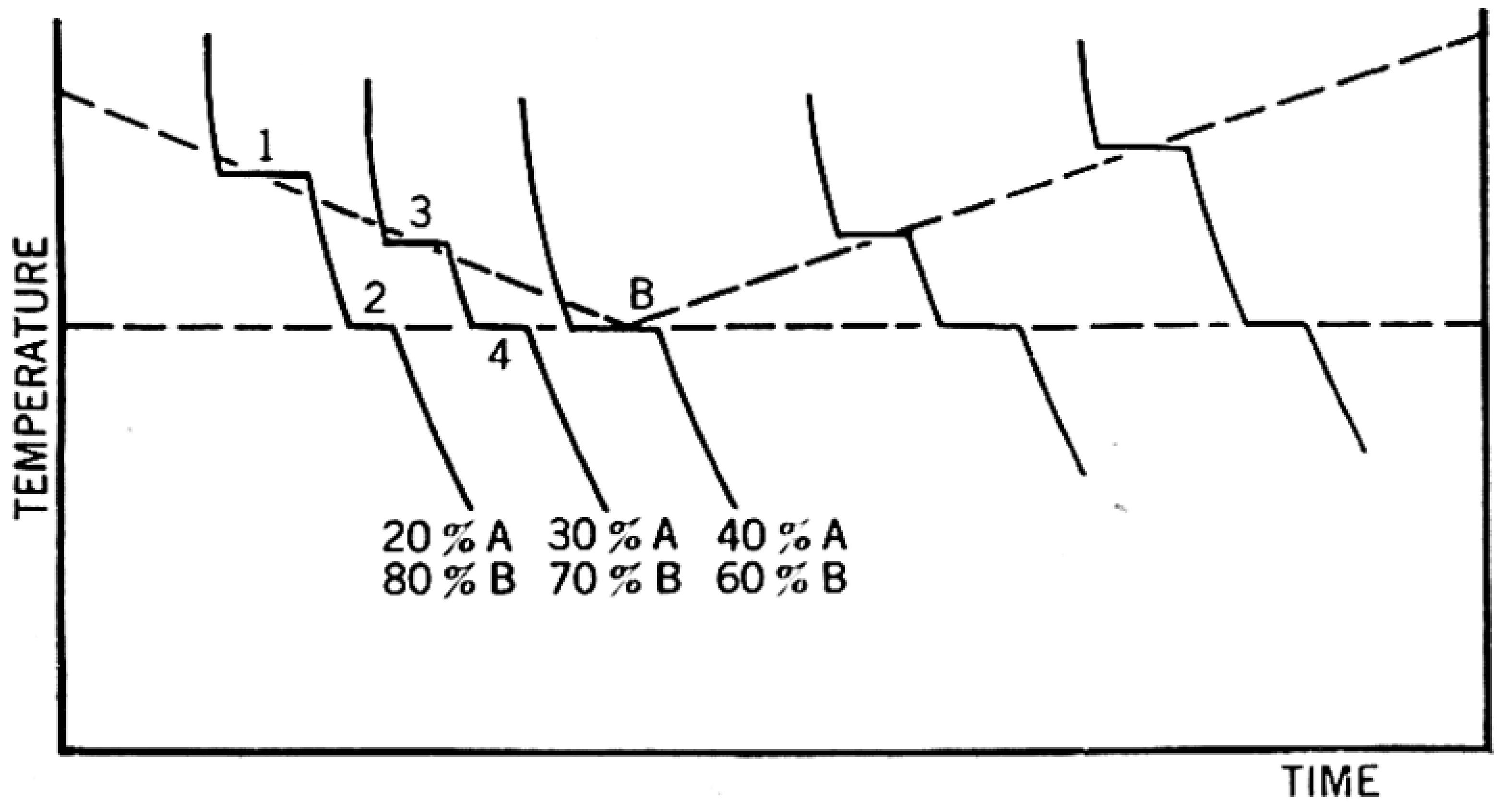


Fig. 5-2. Series of cooling curves of different alloy compositions.

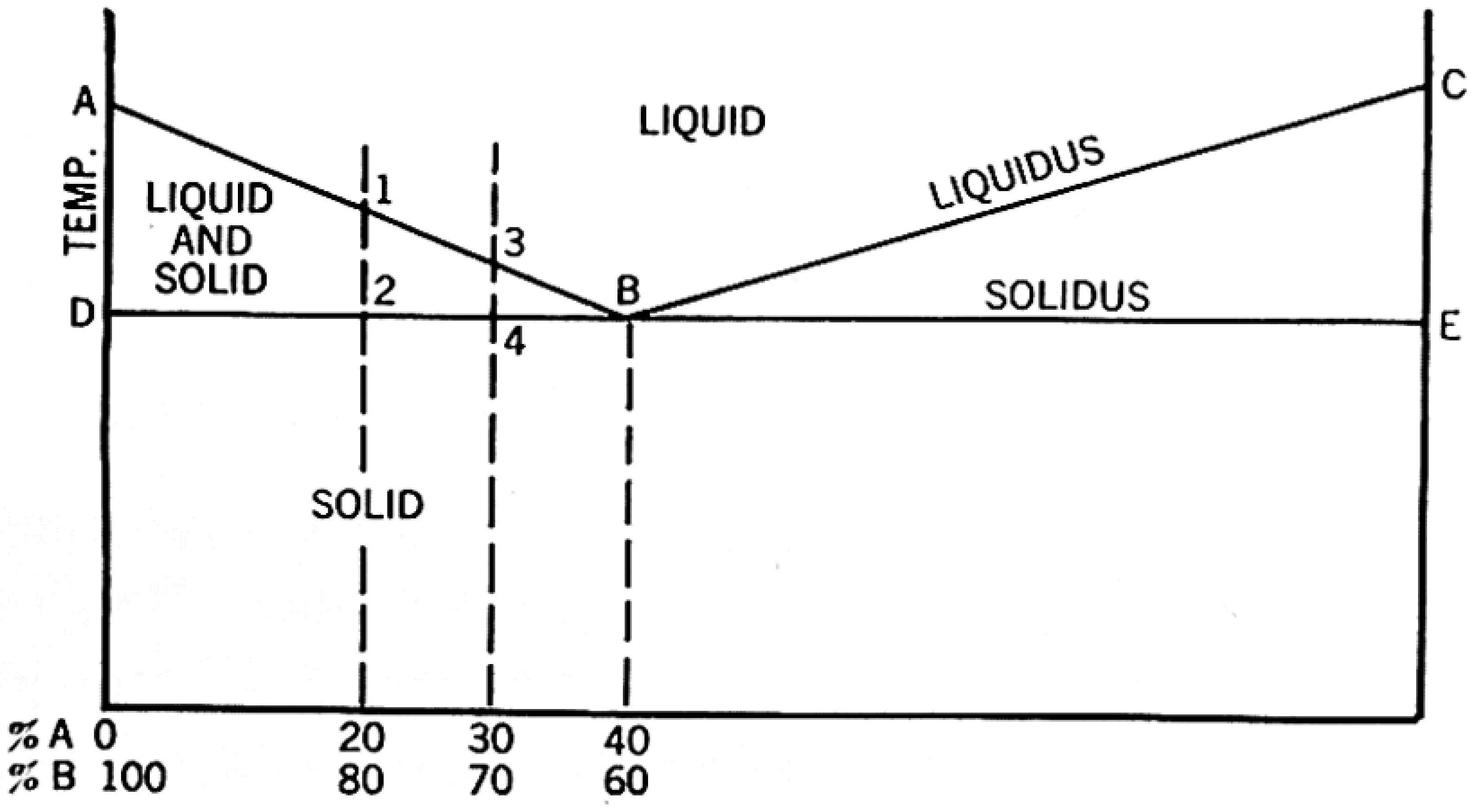


Fig. 5-3. Constitution diagram made from cooling curves in Fig. 5-2.

This regularity suggests the possibility of a new curve of temperature vs. the alloy percentages. Such a curve is shown in Fig. 5-3, where the points *1*, *2*, *3*, and *4* correspond to the points *1*, *2*, *3*, and *4* in Fig. 5-2. It is called an *equilibrium* or a *constitution diagram*. All the material above the line *ABC* is liquid; the line is called the *liquidus*. In between the lines *ABC* and *DBE*, the material is all solid. The line *DBE* is called the *solidus*.

Types of equilibrium diagrams. The study of several general cases of equilibrium diagrams will give a good basis for further study. There are many variations and complications. The general types may be listed in the following manner:

Case I—Insoluble in all proportions in both the liquid and solid states.

Case II—Soluble in all proportions in both the liquid and solid states.

Case III—Soluble in the liquid state only.

Case IV—Soluble in the liquid state and partially soluble in the solid state.

Case V—Soluble in the liquid state and soluble in the solid state within certain temperature ranges.

Case I. Aluminum and lead, and copper and lead are examples of Case I. The diagram for aluminum and lead is shown in Fig. 5-4.

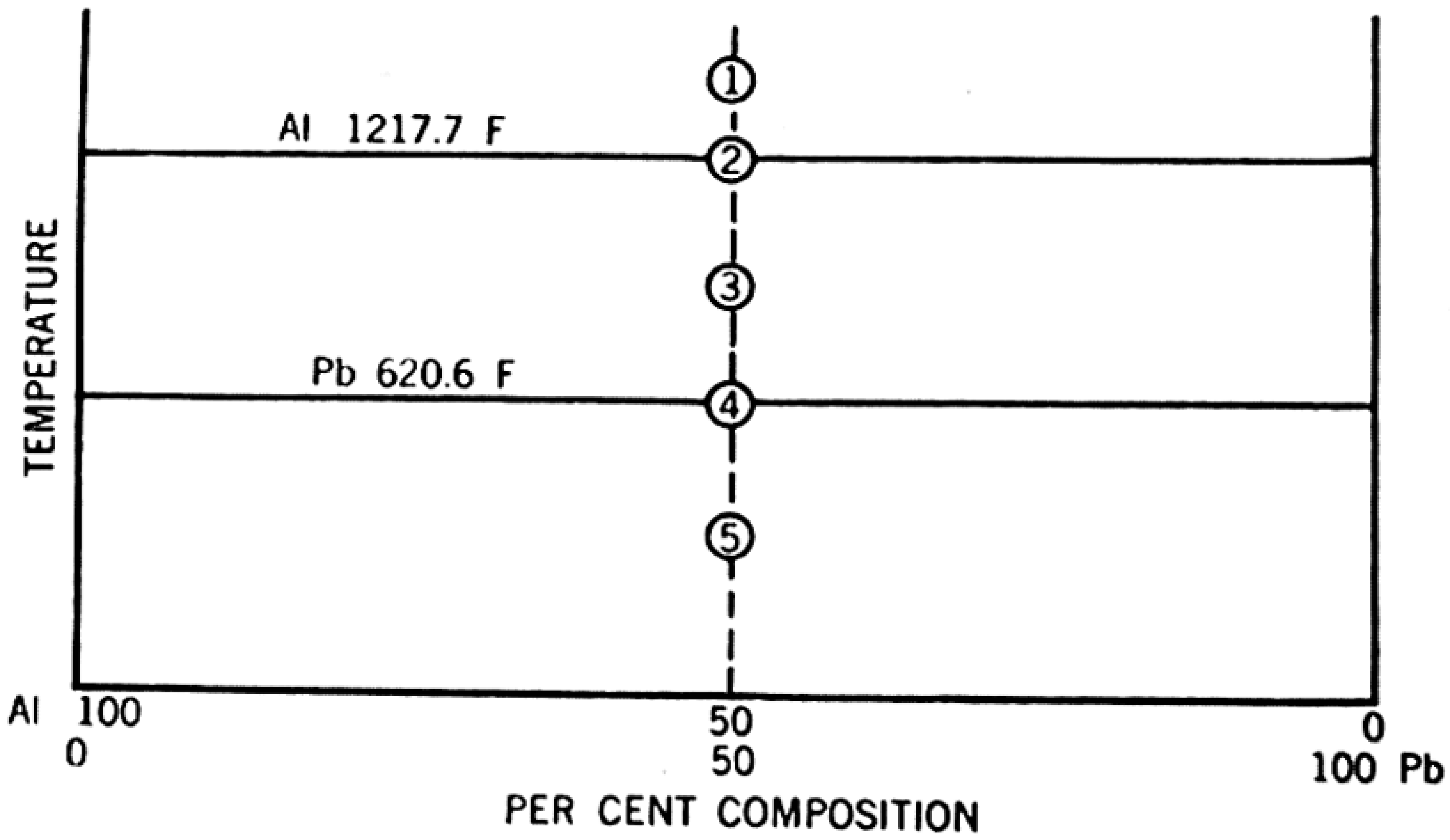


Fig. 5-4. Showing Al-Pb diagram as an example of Case I.

Since no solution occurs in either the solid or liquid state, the solidifying temperature of neither metal is affected by the other. Regardless of the composition, all the aluminum solidifies at 1217.7 F, and all the lead solidifies at 620.6 F. Tracing the changes of the 50–50 mixture, at point *1* both metals are liquids but are not dissolved in each other. When the temperature lowers to point *2*, the aluminum begins to crystallize and float on the heavier lead. After all the aluminum has solidified, the temperature lowers through point *3* to point *4*, where the lead begins to crystallize. The temperature remains at 620.6 F until all the lead has solidified, and then it drops through point *5*, where the Pb and Al are in completely separate crystals. Because of the great difference in specific gravities, the Al floats on the lead and is therefore completely separated, making the so-called alloy of no commercial value. Since copper and lead have more nearly the same specific gravities, they do not tend to separate so completely. In fact, if 15% to 30% lead alloy is cooled fast enough, the lead will be distributed throughout the copper in the form of spherical particles. These *plastic coppers* make good bearing materials.

Case II. This case represents alloys which are soluble in both the liquid and solid states in all proportions, such as the gold-silver, gold-platinum, copper-nickel, iron-nickel, iron-manganese and nickel-chromium alloys. Figure 5-5 represents a typical Case II alloy. Above the liquids, the material is a liquid solution at all proportions of the two metals; below the solidus, it is a solid solution at all compositions. In between these two lines, there is a *mushy* material composed of a mixture of solid-solution crystals and a liquid solution.

The Case II diagram might be more clearly understood by tracing through the changes from point *1* to point *3* in Fig. 5-5. At point *1* there is a liquid solution of *A* and *B*. When the temperature drops to the liquidus, crystals of the solid solution start to form. As the temperature lowers further, more and more crystals form, until the material is completely solid at the solidus. The alloy at point *3* is a solid solution.

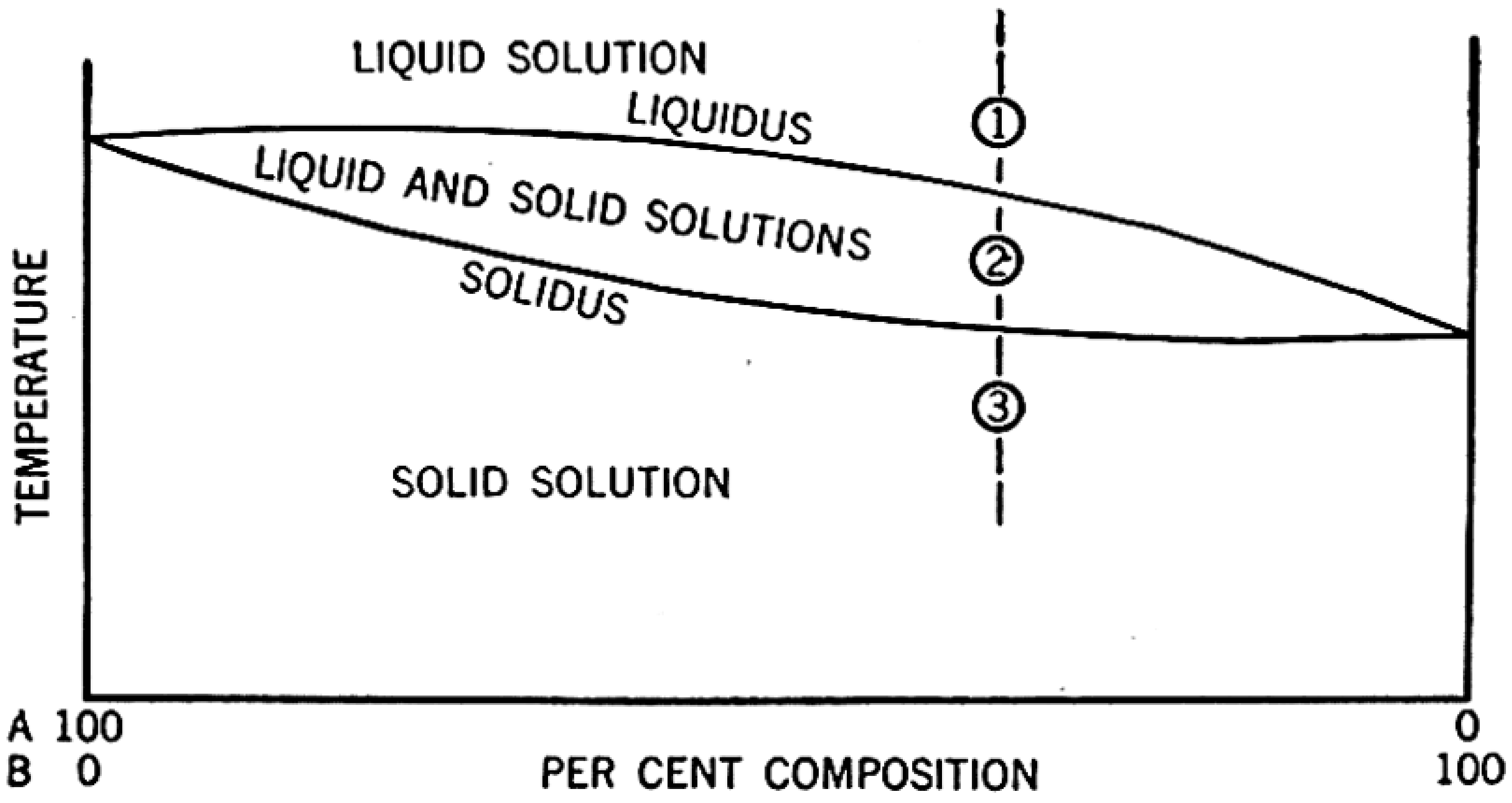


Fig. 5-5. Case II.

Case III. Case III represents alloys which are completely soluble in the molten state and completely insoluble in the solid state. This type is sometimes called an *eutectic diagram*. As a basis for understanding this diagram, it should be understood that, in most cases, when one metal is dissolved in another, the freezing point of the solvent is lowered. An excellent example of this phenomenon is the solution of salt and water. In Fig. 5-6, as more of *B* is added to *A*, the liquidus *CD* goes to lower temperatures. On the other hand, as more of *A* is added to *B*, the liquidus *ED* goes to lower temperatures until it crosses *CD* at *D*. Point *D* then indicates the composition which gives the lowest-melting-temperature alloy. This lowest temperature is called the *eutectic temperature*, and the composition at that point is called the *eutectic alloy*. The point *D* itself is termed the *eutectic point*.

Suppose that the changes in several alloys are traced as the metals cool. At point *1* the material is liquid, but as the temperature reaches the liquidus, metal *A* starts to crystallize as a pure crystal of *A*. When point *2* is reached, the material consists of some crystallized *A* and an enriched solution of *B* in *A*. This process of enrichment continues until the temperature lowers to the solidus. The solidus is a straight, horizontal line which passes through the eutectic point; therefore it represents the lowest temperature at which a liquid may exist. Since the eutectic composition has the lowest possible melting point, it must be that the liquid upon reaching the solidus has been enriched to the eutectic composition. Point *3* is then a solid consisting of crystals of *A* mixed with crystals of the eutectic mixture. Figure 5-7 shows the grain structure of such a composition. The light crystals would be those of metal *A*, and the laminated crystals would be the eutectic mixture. The laminated crystals are made up of alternate layers of the metals *A* and *B* in what is called an *intimate mixture*, as contrasted with a compound. However, this mixture contains very definite percentages of the alloying metals, those at the eutectic point.

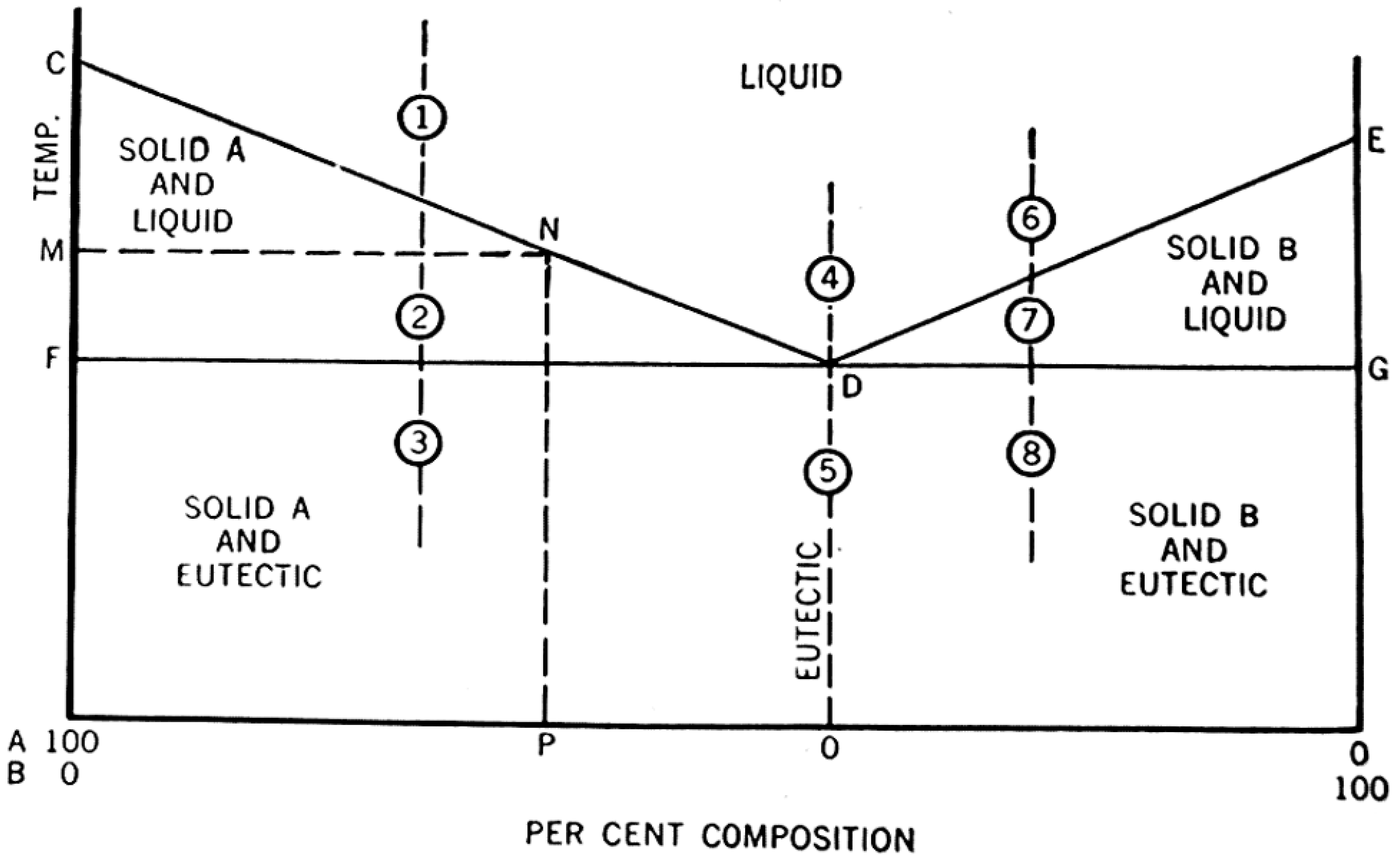


Fig. 5-6. Case III.

Following the changes from point 4, where the metals are molten, no change takes place until point *D* is reached. Since this is the eutectic point, all the material crystallizes at that temperature, forming a solid of 100% eutectic crystals at point *5*. Figure 5-8 shows this grain structure. When the liquid at point *6* cools to the liquidus, crystals of metal *B* start to crystallize out. As the temperature passes through point *7*, the liquid becomes more enriched, until the eutectic composition is reached at the solidus, at which temperature the remaining liquid becomes crystals of the eutectic composition. At point *8* there are crystals of *B* mixed with crystals of the eutectic, as shown in Fig. 5-9.

Examples of Case III are the bismuth-cadmium and the lead-antimony alloys.

Principle of horizontals. The liquidus *CDE* in Fig. 5-6 constitutes a line of balancing conditions in the changes of state. If a slight amount of heat is added, metal melts; if it is subtracted, metal freezes. It is a line of equilibrium. Therefore these diagrams are called *equilibrium diagrams*.

Consider the horizontal line *MN* through point *2*. The point *N* is the equilibrium temperature for the composition *P*. The line *MN* is also

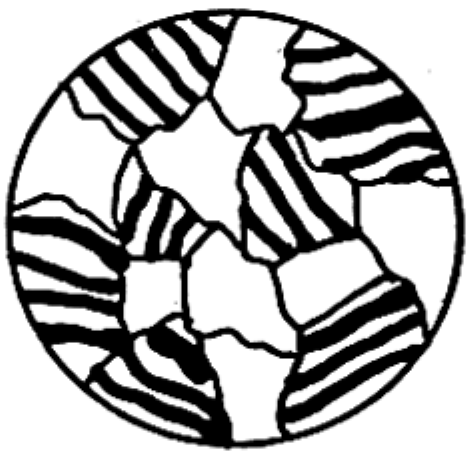


Fig. 5-7. Below eutectic per cent of *B*. Light crystals are *A*, laminated are eutectic.

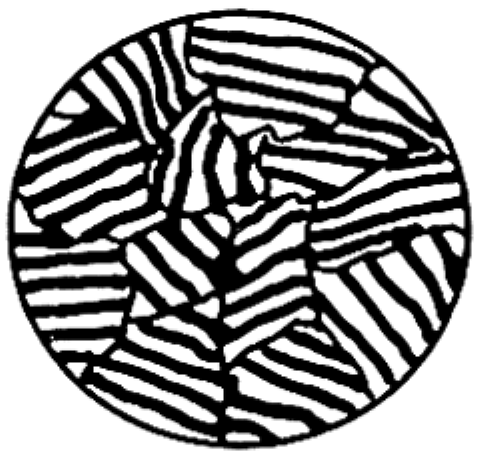


Fig. 5-8. One hundred per cent eutectic.

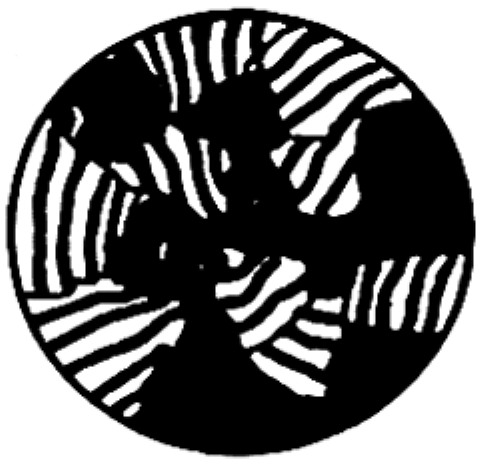


Fig. 5-9. Above eutectic per cent of *B*. Dark crystals are *B*.

an equilibrium line, since the addition of heat will cause crystals of metal *A* to melt, and the subtraction of heat will cause crystals of *A* to separate from the liquid. The composition *P* must then represent the composition of the remaining liquid for any alloy at the temperature of the line *MN*. This concept is known as the *principle of horizontals*, which states that *the composition at all points along a horizontal temperature line in any one block of an equilibrium diagram is constant.*

This principle makes it possible to figure the amounts of solid and liquid at any given point in a block. For instance, suppose that the composition at point *1* were 70% *A* and 30% *B*, and that the composition at *N* were 50% *A* and 50% *B*. Also assume that the total material weighs 100 lb.

At point *1* there is 70 lb of *A* and 30 lb of *B*. At point *2* there is still 30 lb of *B* in the liquid, but some of the *A* has crystallized out. Since by the principle of horizontals the composition of the liquid at point *2* is 50% *A* and 50% *B*, there must be 30 lb of *A* in the liquid. Therefore, there must be 60 lb − 30 lb = 30 lb of *A* in crystalline form at point *2*. Now assume that the eutectic alloy composition is 40% *A* and 60% *B*.

To find the proportions of material in the solid state at point *3* proceed as follows:

There is 30 lb of *B* in the eutectic composition. Therefore, the amount of *A* would be

$$\frac{A}{30 \text{ lb}} = \frac{40}{60}$$

$$A = \frac{40 \times 30 \text{ lb}}{60} = 20 \text{ lb of metal } A$$

The amount of eutectic = 30 lb + 20 lb = 50 lb. The amount of excess *A* = 100 lb − 50 lb = 50 lb. Therefore, at point *3* there is 50% crystalline *A* and 50% eutectic crystals.

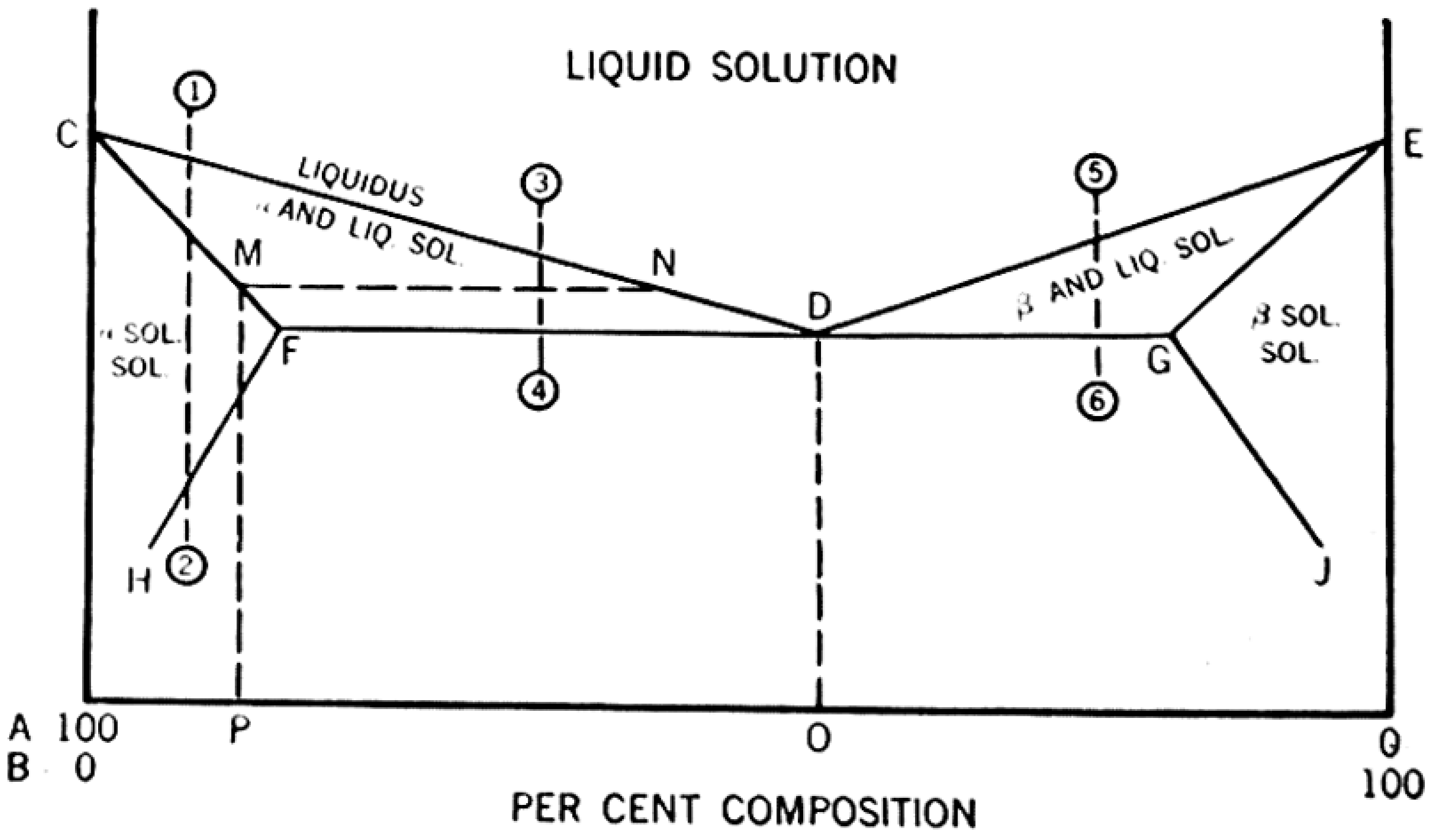


Fig. 5-10. Case IV.

Case IV. In Case IV the metals are soluble in each other in the liquid state but only partially soluble in the solid state. Above the line *CDE* in Fig. 5-10 a liquid solution exists. The variation of the remainder of the diagram from that of Case III is the blocks of solid solution. The left-hand block is generally termed *α solution*, and the other side is *β solution*.

The principle of horizontals can be used to help determine the character of the material in the block *HFDO*. The horizontal *MN* does not extend to the pure metal line of 100% *A* at the left, but first hits the line *CF*. The line *CF* indicates an α solid solution; therefore, the solid in block *CDF* is an α solid solution of composition *P*. On the right side, the solid in block *DEG* is a β solid solution for similar reasons. The eutectic must therefore consist of a mixture of α and β solid solutions. One can now see that block *HFDO* consists of α solution and an eutectic of α and β solutions, while block *DGJO* consists of β solution and an eutectic of α and β solutions.

Trace the change from point *1* to point *3*. At point *1* there is a liquid solution. As the temperature lowers to the line *CD*, α solid solution starts to appear and at line *CF* it is 100% α solution. At line *FH* the solution is saturated. If the temperature is lowered still more, either *B* must come out of solution or else the solution is supersaturated and unstable. Use is made of the supersaturated condition in the precipitation-hardening process. In order to reach a stable condition at point *2*, enough metal *B* must come out of solution so that the solution is not supersaturated. In the process of leaving the α solution, the particles of *B* strain the crystals, thus hardening and strengthening the material. This type of hardening, called *precipitation-hardening*, will be discussed in a later chapter.

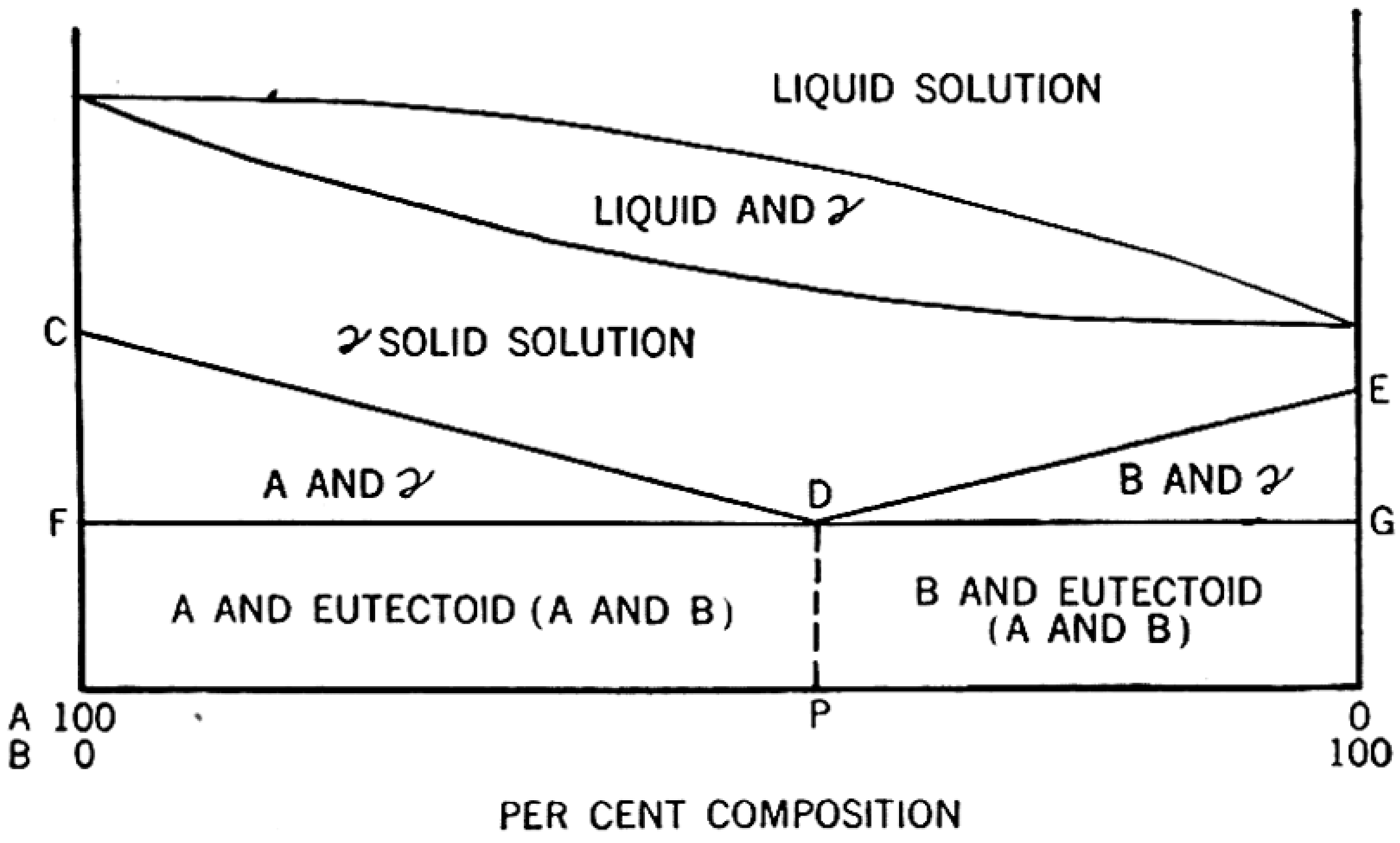


Fig. 5-11. Case V.

The changes from point *3* to *4* are somewhat different from the corresponding points in Case III. At the liquidus, α solution starts to crystallize out instead of the pure metal *A*. As the temperature lowers to the line *FD*, enough α solution crystallizes out of the liquid to make the eutectic mixture of α and β solutions. The remaining liquid then solidifies at the eutectic temperature. At point *4*, the material consists of the eutectic mixture of α and β solutions and an excess of α solid solution. The changes from point *5* to point *6* are similar to those from point *3* to *4*, except that the excess of β crystallizes out so that the material at point *6* consists of the eutectic plus an excess of β solution.

A practical example of Case IV is the lead-tin series of alloys. These alloys form the different types of solder. The lead-tin eutectic contains about 38% lead and is called *tin solder*. Since it is eutectic, the solder changes from a liquid to a solid quickly. *Plumbers' solder*, which contains about 67% lead, passes through a mushy stage as the lead-rich crystals form. The cooling through the mushy state requires time, which gives an opportunity for *wiping* the joints of the lead sheaths of telephone and electric power cables.

Case V. Case V represents alloys of metals which are soluble in the liquid state and soluble in the solid state within certain temperature limits. A study of Fig. 5-11 reveals that the upper part of the diagram is similar to Case II, but as the temperature lowers to line *CDE*, pure crystals of the metals *A* and *B* come out of solution. The point *D* is the lowest temperature at which a 100% solid solution is possible, and since no change of state occurs in passing through this point, it is called the *eutectoid.* At the line *FDG*, then, all the remaining γ solution breaks down into a eutectic mixture of *A* and *B*. This case can be used to explain the iron-carbon system.

Other diagrams. It should be understood that the five cases just described are the simpler types. However, many variations and combinations of these types exist. The formation of intermetallic compounds often causes instability of solutions so that the diagrams are complicated. More advanced texts can provide more detailed information on these diagrams. Three-dimensional and contour diagrams can be used to illustrate simple ternary alloy changes.

SUMMARY AND DEFINITIONS

The five simplified types of constitution diagrams of binary alloys are:

Case I. Insoluble in all proportions in both the liquid and solid states.

Case II. Soluble in all proportions in the liquid and solid states.

Case III. Soluble in the liquid state and partially soluble in the solid state.

Case IV. Soluble in each other in the liquid state but only partially soluble in the solid state.

Case V. Soluble in the liquid state and soluble in the solid state within certain temperature ranges.

Cooling curve. A curve having the temperature of a material as its ordinate and time as its abscissa.

Binary alloy. An alloy consisting of *two* pure metals and possibly minor impurities.

Ternary alloy. An alloy consisting of *three* pure metals and possibly minor impurities.

State. The condition of a material, such as solid, liquid, or gas.

Liquidus. The line on an equilibrium diagram above which all the metal is molten.

Solidus. The temperature line on an equilibrium diagram below which all the metal is solid.

Mushy stage. The blocks between the liquidus and the solidus where the material is partly liquid and partly solid.

Eutectic. The lowest temperature at which an alloy can be completely liquid.

Eutectoid. The lowest temperature at which a solid solution is possible.

Equilibrium diagram. A diagram showing the transformation temperatures for all compositions of a given metal alloy series.

Constitution diagram. Another name for an equilibrium diagram.

The principle of horizontals. States that the composition at all points along a horizontal temperature line in any one block of an equilibrium diagram is constant.

PROBLEMS

1. Explain how the data for a cooling curve may be obtained.
2. How are cooling curves used in the construction of equilibrium diagrams?
3. Explain carefully how the equilibrium diagram gets its name.
4. How can the principle of horizontals be used to determine the percentage of eutectic in an alloy?
5. Discuss fully the practical use of an equilibrium diagram.
6. If the eutectic in Fig. 5-6 were 60% *A* and 40% *B*, how many pounds of eutectic and of solid *A* would there be in 100 lb of alloy of 30% *A* and 70% *B*?
7. Do Problem 6 with an alloy of 40% *A* and 60% *B*.

Chapter 6

THE IRON-CARBON CONSTITUTION DIAGRAM

PERHAPS THE most important of all alloy series is the iron-carbon series, and this is commercially important only under about 5% carbon. This chapter will deal with that portion of the equilibrium diagram.

Iron-carbon equilibrium diagram. The iron-carbon diagram has been a subject of investigation for many years and the critical temperatures have been fairly well determined. Figure 6-1 is a simplified equilibrium diagram of this series of alloys which shows only the iron-rich end up to about 5% carbon. Certain changes near *H* are omitted, since they are unnecessary in this book. The liquidus is the line *HDE* and the solidus is the line *HCDK*. The section of the diagram between 0% and 1.7% carbon is the steel section, which will be discussed more fully in the next chapter, and the remainder represents the cast irons.

The point *D* is the eutectic for iron and carbon, which is at about 4.3% carbon. It is interesting to note that this is about the composition of the blast-furnace pig iron. Point *B* is the eutectoid.

Two allotropic forms of iron are of interest in this book. They are termed alpha (α) iron and gamma (γ) iron. The cause of the differences in these metals of the same element is the atomic arrangement in the crystals. Alpha iron is body-centered (Fig. 6-2a), and gamma iron is face-centered, that is, γ iron is more closely packed and therefore of somewhat higher density than α iron. (Fig. 6-2b.)

Among the more important distinguishing characteristics between alpha iron and gamma iron are the magnetic and solution properties. Alpha iron is magnetic, whereas gamma iron is para-magnetic. Alpha iron dissolves only very small amounts of carbon, whereas gamma iron disolves up to 1.7% carbon. Solutions in which alpha iron is the solvent are termed *ferrite*. Ferrite is almost pure iron. Solutions in which gamma iron is the solvent are termed *austenite*.

Phases and constituents. A *phase* can be defined as a physically distinct, homogeneous substance. Applied to metallurgy, each of the

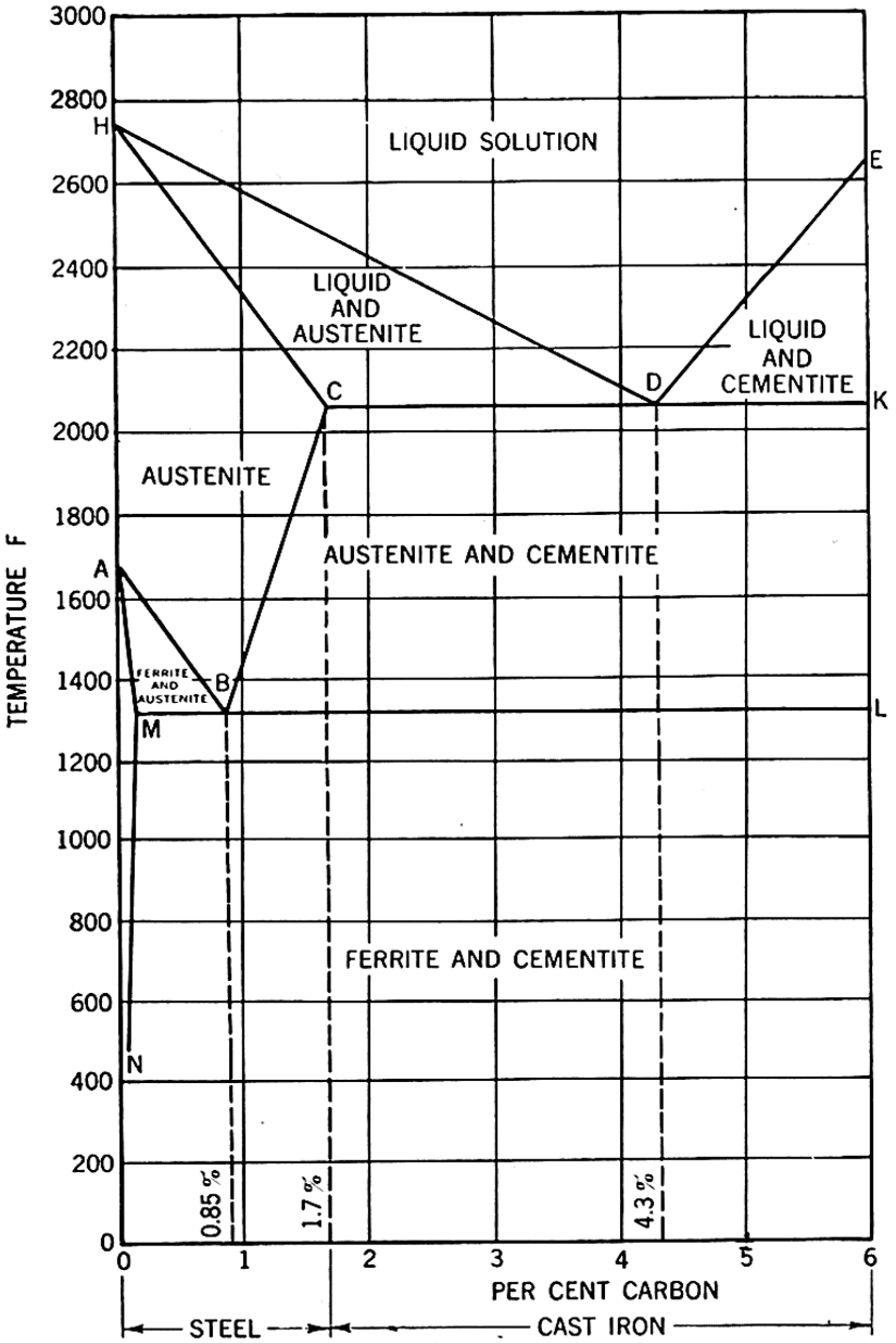


Fig. 6-1. Simplified diagram of iron-carbon alloys.

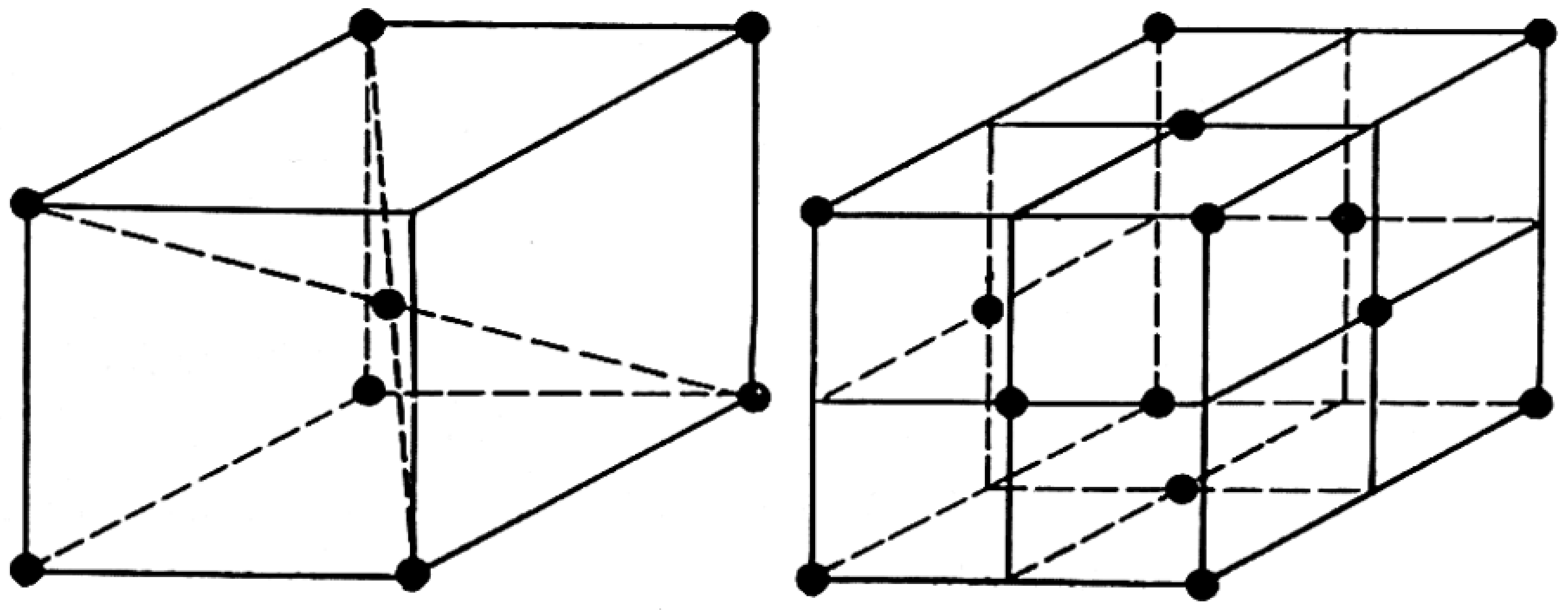

(a) (b)

Fig. 6-2. (a) Body-centered lattice. (b) Face-centered lattice.

following may be considered a separate phase: pure metal, metallic compound, solid solution, liquid, solid, and gas.

Constituents are those portions of an alloy which appear to be definite units in the structure when viewed through a microscope. They may include eutectoid mixtures which appear to be homogeneous at low magnifications but are in reality mixtures.

All phases are constituents, but not all constituents are phases, since some are mixtures. Austenite and ferrite are phases, whereas pearlite is a constituent but not a phase.

Except for variations near *H*, austenite freezes out of the liquid from the line *HD* to *HC*. At *HC* the alloy becomes one solid phase, austenite. At *CD* the remaining liquid is the eutectic composition. This liquid freezes at a constant temperature into the eutectic mixture of austenite and cementite known as *ledeburite*. Cementite freezes out of alloys containing more than 4.3% carbon from *DE* to *DK*. At *DK* the remaining liquid has the eutectic composition which freezes into ledeburite at a constant temperature.

The temperature at which gamma iron changes to alpha iron (ferrite) lowers as the percentage of carbon in austenite increases. The line *AB* represents this change. As ferrite continues to form, it leaves a carbon-enriched austenite; therefore the temperature must lower before more ferrite can form. The line *AB* indicates the solubility of ferrite in austenite, and is therefore known as the *ferrite solubility curve.*

The line *BC* is called the *cementite solubility curve* since it is the line at which the cementite phase is precipitated. Beyond point *B*, about 0.85% carbon, the increasing percentage of carbon dissolved in austenite raises the temperature at which cementite precipitates. Conversely, when the temperature is continuously lowered to line *BL*, increasing amounts of cementite, and therefore carbon, leave the austenite until the line *BC* crosses *AB*. Point *B* must then indicate the temperature at which austenite is saturated with both cementite and ferrite. No further reduction in temperature is possible if austenite is to be retained. The remaining austenite becomes the eutectoid mixture upon cooling below this temperature.

If the cooling is sufficiently slow, the eutectoid mixture solidifies into grains which consist of alternate layers of ferrite and cementite. These grains are known as *pearlite,* because of their appearance. The phases below the line *ML* are cementite and ferrite, and part of these phases form the eutectoid constituent, pearlite.

The block *AMN* exists in only very low-carbon-content steels, which are not common materials. It does, however, resemble Case IV, in which precipitation-hardening is possible. The existence of block *AMN* explains the slow hardening of ferrite which sometimes occurs at room temperatures. It also indicates that ferrite is a solid solution which contains a small amount of carbon, possibly from 0.01% to 0.035%.

Certain phases exist in a stable condition in certain blocks in Fig. 6-1. The following is a list of the phases in the more important blocks:

Above *HDE*—liquid solution
HDC—liquid solution and austenite
DEK—liquid solution and cementite
HCBA—austenite
ABM—ferrite and austenite
BCKL—austenite and cementite
Below *ML*—ferrite and austenite.

Calculation of compositions. Figure 6-1 can be used as a basis for calculating the compositions of the various constituents of steel. The amount of Fe_3C is the starting point of the calculations. The atomic weight of iron is approximately 56; that of carbon is 12: therefore, there are 3 × 56 parts of iron to 12 parts of carbon by weight. Thus the percentage of carbon in Fe_3C is approximately

$$\frac{12}{3 \times 56 + 12} \times 100 = 6.6\%$$

In pearlite, it is known that the ratio by weight of the Fe_3C laminations to the Fe laminations is about 1 to 7, a fairly constant ratio if impurities are small. Suppose 0.3% carbon-steel is being figured, and suppose that all the carbon is in the Fe_3C, then the percentage of Fe_3C is $\frac{0.3}{0.066} = 4.5\%$ of the total steel. Also, since all the Fe_3C is in the pearlitic laminations, the percentage of pearlite is $4.5\% \times 7 = 31.5\%$, and the percentage of ferrite is $100 - 31.5 = 68.5\%$.

Consider a steel having 1.2% carbon content. The amount of Fe_3C is $\frac{1.2\%}{0.066} = 18.2\%$. If 18.2% of the steel is Fe_3C, the remainder must be ferrite, the percentage of which is $100\% - 18.2\% = 81.8\%$. Above the eutectoid percentage of carbon, all the ferrite is in the ferrite laminations of pearlite; therefore there must be $\frac{8}{7} \times 81.8\% = 93.5\%$ of pearlite. The remainder of the steel is the excess cementite, which is $100\% - 93.5\% = 6.5\%$.

Definitions and Summary

Alpha iron (α) has a body-centered lattice.

Gamma iron (γ) has a face-centered lattice and is para-magnetic.

Ferrite is almost pure alpha iron, although alpha iron will form a solid solution with silicon, nickel, phosphorous, and small amounts of carbon.

Cementite is iron-carbide (Fe_3C) and it can be dissolved in gamma iron.

Austenite is a solid solution of gamma iron and cementite or carbon.

Pearlite is the eutectoid decomposition product of slowly cooled austenite. Structurally, it consists of alternate layers of ferrite and cementite.

A **phase** is a physically distinct, homogeneous substance. A separate phase may be a pure metal, a metallic compound, a solid solution, a liquid, a solid, or a gas.

A **constituent** is that portion of an alloy which appears to be in definite units in the structure when viewed through a microscope. Pearlite, although a mixture, is a constituent, since it appears to be homogeneous at low magnifications. All phases are constituents, but not all constituents are phases.

Ledeburite is the eutectic mixture of iron and carbon. It consists of austenite and cementite.

PROBLEMS

1. Distinguish between a phase and a constituent.

2. What methods can be used to determine when alpha iron has changed to gamma iron?

3. What is meant by the term "solubility curve"?

4. What are the main differences between austenite and ferrite?

5. Trace and describe the changes in 0.6% carbon-steel as it is cooled slowly from a liquid to room temperature.

6. By studying Fig. 6-1 find the maximum percentage of carbon that can be dissolved in gamma iron.

7. Calculate the percentages of ferrite, cementite, and pearlite in 0.4% carbon-steel.

8. Calculate the percentages of ferrite, cementite, and pearlite in 1.0% carbon-steel.

Chapter 7

THE HEAT-TREATMENT OF STEEL

THE GREAT usefulness of steel depends not only upon its cost and strength, but also upon the variety of properties obtainable by heat-treatment. This chapter deals with the heat-treatment of carbon-steel.

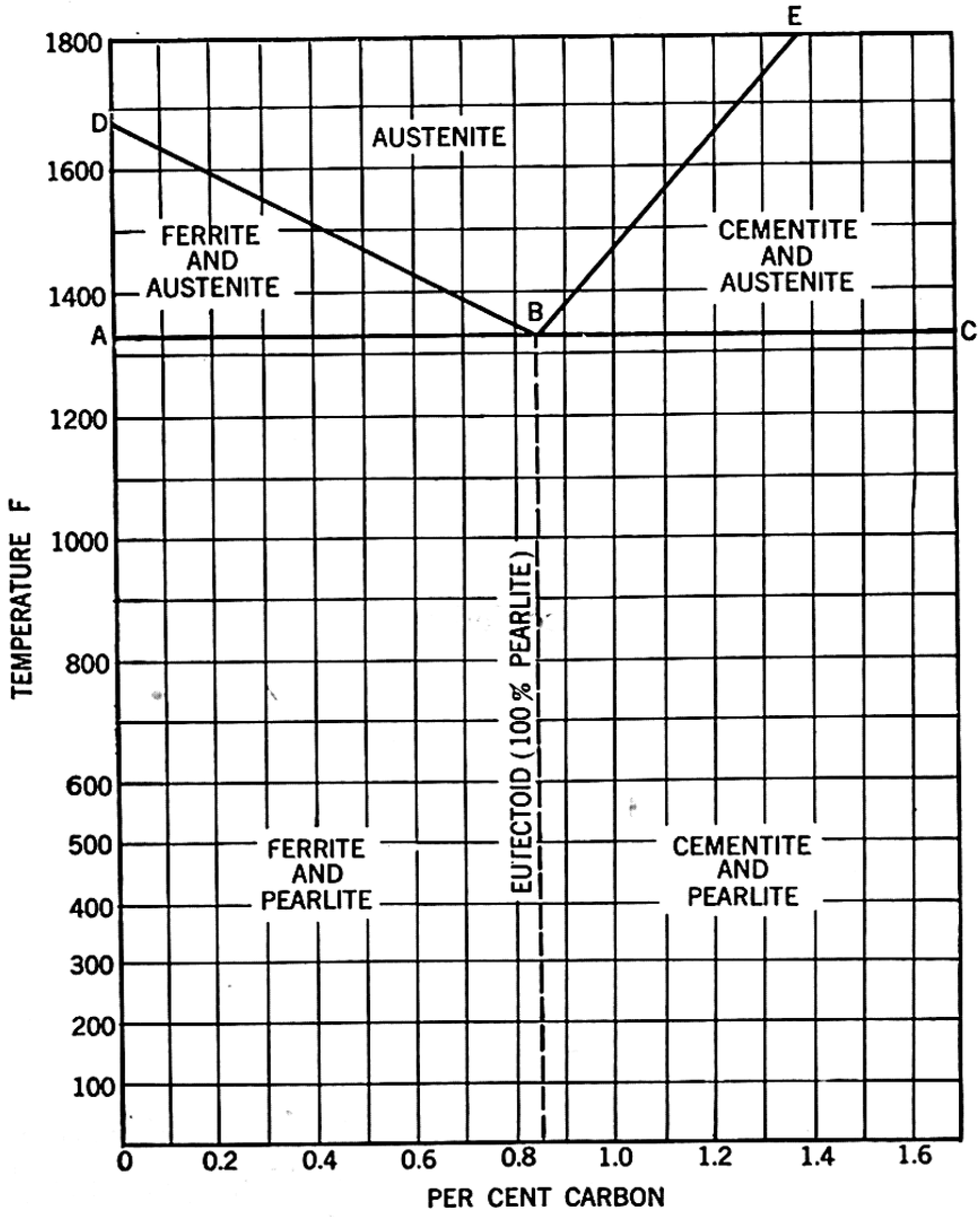


Fig. 7-1. Steel portion of the simplified iron-carbon constitution diagram.

Steel. Steel is generally considered to be confined to the iron-carbon alloys containing between about 0.05% and 1.7% carbon. The actual useful steel is even more limited. Figure 7-1 shows a simplified constitution diagram of the solid steel portion of the iron-carbon diagram.

The phases encountered in the heat-treatment of steel are austenite, ferrite, and cementite.

Austenite. Austenite is found in stable form only above the line *ABC*. Since it is a solid solution, the grains appear to be homogeneous when viewed through the most powerful microscopes. Since it is paramagnetic, the temperature at which all the metal is austenite (that is, the upper critical temperature lines *DBE*) may be detected by the use of a magnet.

The maximum solubility of carbon in gamma iron is 1.7% at a temperature of 2066 F. Austenite has no definite composition such as cementite has.

Ferrite. Ferrite is nearly pure alpha iron. It can be found anywhere below the 1333 F line *ABC*, along with other crystals. It is also found in block *ABD* with austenite. The properties of ferrite at room temperature are:

Tensile strength: 40,000 psi
Brinell hardness: about 90
Elongation: about 40%
Machinable
Strongly magnetic.

Cementite. Cementite is the chemical compound Fe_3C, which has a definite composition. In slowly cooled steel it is found as free cementite in steel containing over 0.85% carbon and as a part of pearlite. In quenched steels it is found in many more complex constituents, which will be described later. The properties of cementite are:

Tensile strength: unknown
Brinell hardness: about 650
Practically no ductility
Magnetic.

Primary constituents. The products of quenched austenite are known as the *primary constituents* of steel. They are generally put into four groups: *martensite*, *primary troostite*, *sorbite*, and *pearlite*. The product that is obtained by quenching depends mainly upon the rate of cooling and the temperature to which it was cooled, but it can also depend upon the grain size of the austenite and the temperature at which the cooling starts. Large grains tend to slow up the transformation from austenite to the decomposition product. Thus they have the same effect as slower cooling.

Martensite. Martensite is the decomposition product which results from the very rapid cooling of austenite. The lower the carbon content of the steel, the faster must be the cooling in order to obtain martensite. Under the microscope it appears as needle-like crystals placed at random. It is the hardest of the primary constituents. The properties of martensite are:

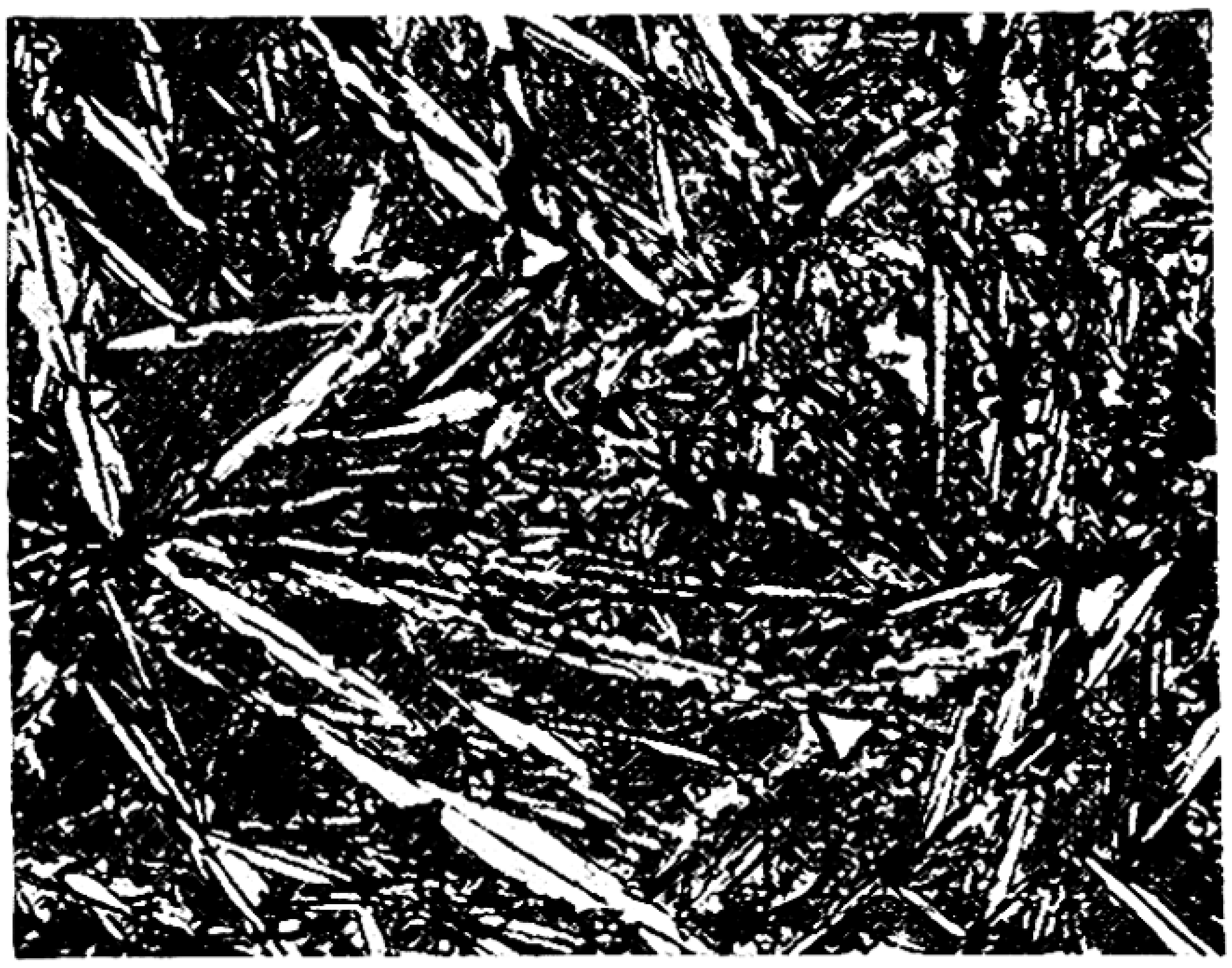


Fig. 7-2. Martensite.

Tensile strength: about 200,000 psi
Brinell hardness: 400 to 700
Elongation: below 10%
Magnetic.

Primary troostite. Primary troostite results from a somewhat slower cooling than that used for obtaining martensite. Primary troostite is very difficult to obtain by itself, since it generally occurs with some martensite if the cooling is too fast and with some sorbite if the cooling is too slow. Under the normal magnifications, troostite appears as dark, irregularly shaped areas or grains, but some observers feel that it has a very fine pearlitic structure.

The properties of primary troostite are:

Tensile strength: less than martensite
Brinell hardness: less than martensite
Ductility: greater than martensite
Machinability: better than martensite.

Primary sorbite. Sorbite is formed with a somewhat slower quench than that used for primary troostite. Under high magnification it appears to have small grains made up of fine laminations similar to those of pearlite. The cooling is too fast to allow the normal pearlitic structure to take form. The properties of sorbite are:

Tensile strength: 90,000 psi
Brinell hardness: about 200
Elongation: about 20%
Machinability: better than troostite.

Pearlite. Pearlite forms upon a very slow cooling of austenite. A complete transformation takes place because time is allowed for the energy changes and the molecular arrangements to take place before rigidity sets in. It appears under the microscope as grains consisting of alternate layers of cementite and ferrite. A study of the iron-carbon equilibrium diagram at about 0.85% carbon indicates that the composition of the cold steel would be 100% pearlite (eutectoid mixture). If the percentage of carbon is less than 0.85%, there will be an excess of ferrite, and if over 0.85%, there will be an excess of cementite. The following steel classifications are based upon the foregoing facts:

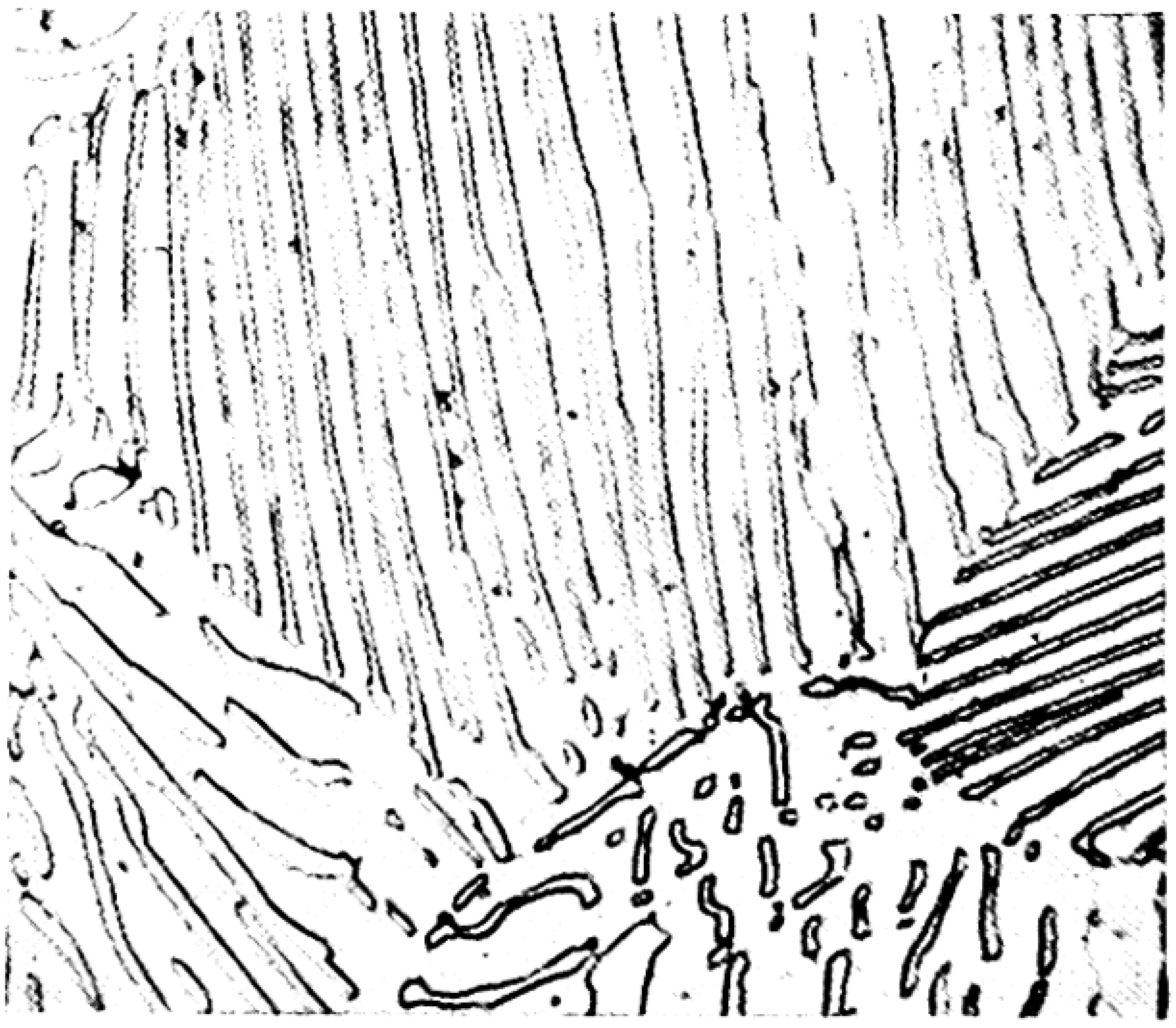


Fig. 7-3. Pearlite.

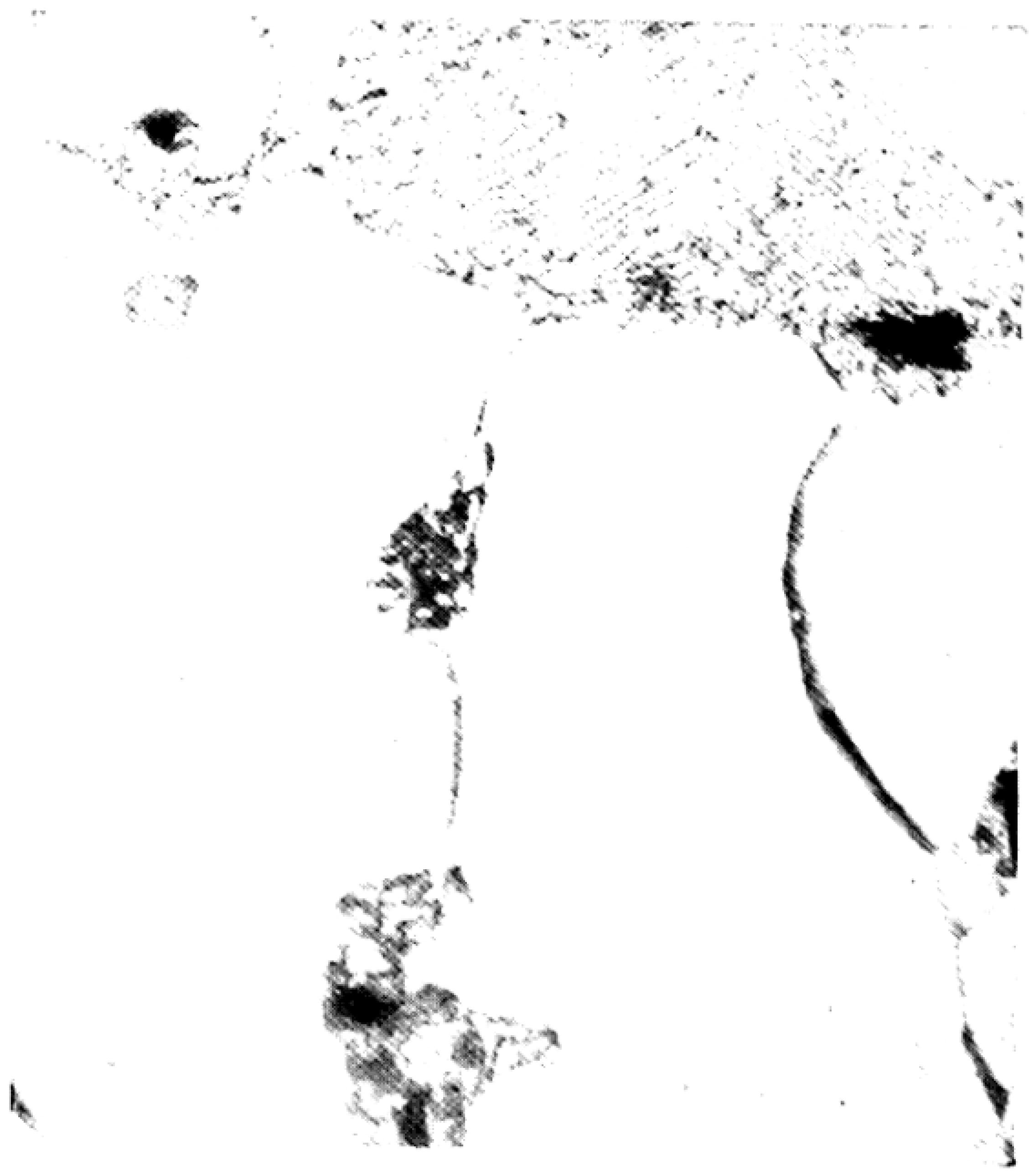


Fig. 7-4. Hypoeutectoid steel.

Hypoeutectoid steel—excess of ferrite

Eutectoid steel—all pearlite

Hypereutectoid steel—excess of cementite.

When the weights of ferrite, cementite, and pearlite are plotted as ordinates against the percentage of carbon in the steel, Fig. 7-6 will result. At 0% carbon, the metal is 100% ferrite, but as the percentage of carbon increases, more cementite is formed. The cementite, in turn, mixes with more ferrite to form more pearlite. At 0.85% carbon, the percentage of cementite is just the correct amount so that all the ferrite has been used in making cementite or will appear as layers of ferrite in pearlitic grains. There is 100% pearlite at the point. An increase in the amount of carbon increases the amount of cementite by taking ferrite from the pearlite. This excess of cementite is caused, firstly, by the new formation, and secondly, by taking ferrite from pearlite and leaving an excess of cementite.

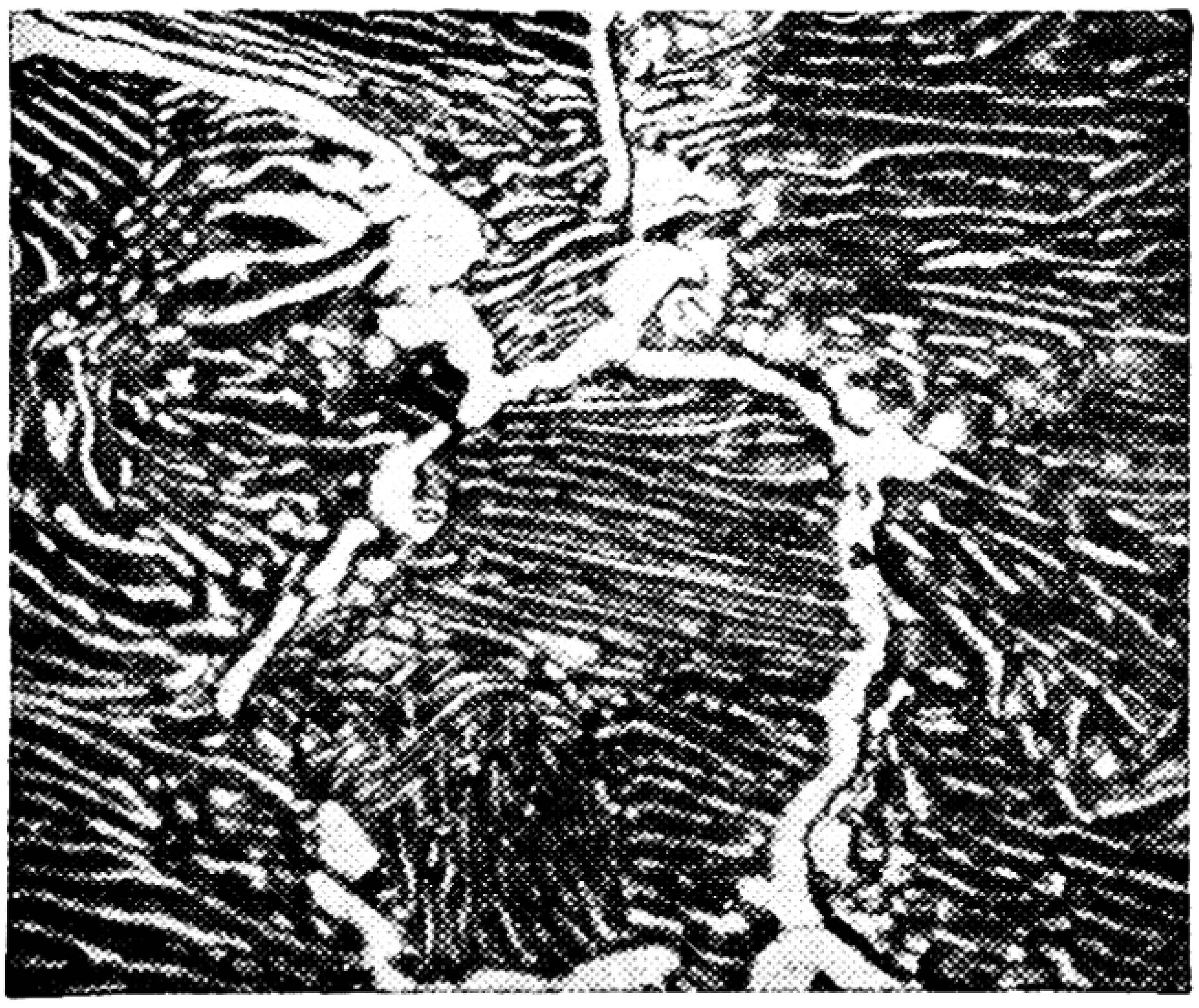


Fig. 7-5. Hypereutectoid steel.

The properties of pearlite are:

Tensile strength: about 100,000 psi

Brinell hardness: about 150

Elongation: about 25%

Machinability: good

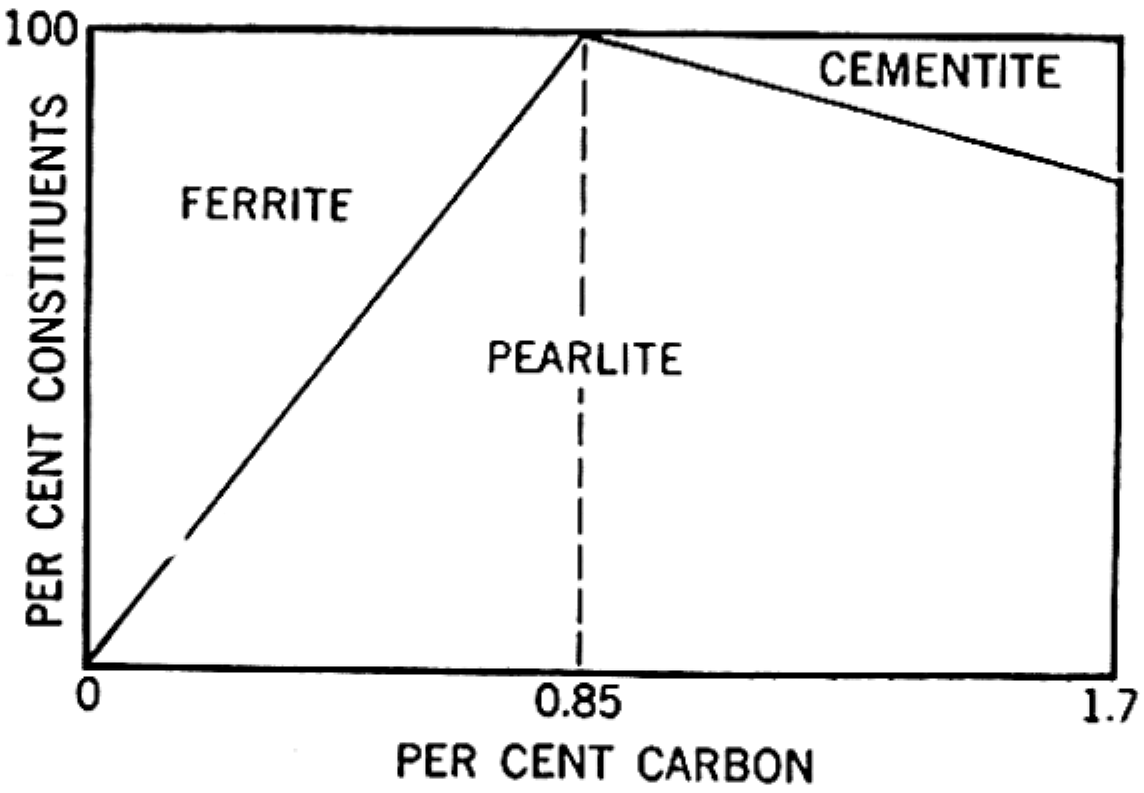


Fig. 7-6. Diagram showing the compositions of slowly cooled steel.

Secondary constituents. The secondary constituents of steel are formed by heating martensite to temperatures below the line ABC (1333 F) and then cooling. The effect of heating in this way is to relieve internal stresses and to increase ductility. This process is known as *tempering* or *drawing*. Since martensite is the most unstable product of the decomposition of austenite, it tends to continue the decomposition process which the fast cooling arrested. The process is speeded up at elevated temperatures and becomes more complete if given more time.

The various products of the decomposition of martensite are called the *secondary constituents* of steel. The product obtained depends upon the temperature and the length of time that the piece is held at the tempering temperature. Increasing tempering temperatures tend to cause the following trends in the physical properties of carbon-steel:

Ductility increases
Hardness decreases
Tensile strength decreases
Machinability increases
Cementite particles increase in size.

The change with temperature is so gradual that no sharp demarcation exists between any of the secondary constituents of steel, namely, *secondary troostite*, *sorbite*, and *spheroidized cementite*. Quenching is not necessary in the tempering process unless a piece is heated in such a way that the temperature continues to rise after heat is no longer applied. This continued rise might occur in the tempering of a center punch where the shank of the punch is heated and the heat is then allowed to travel to the point. When the point is at the correct temperature, as shown by the oxide color, it is quenched.

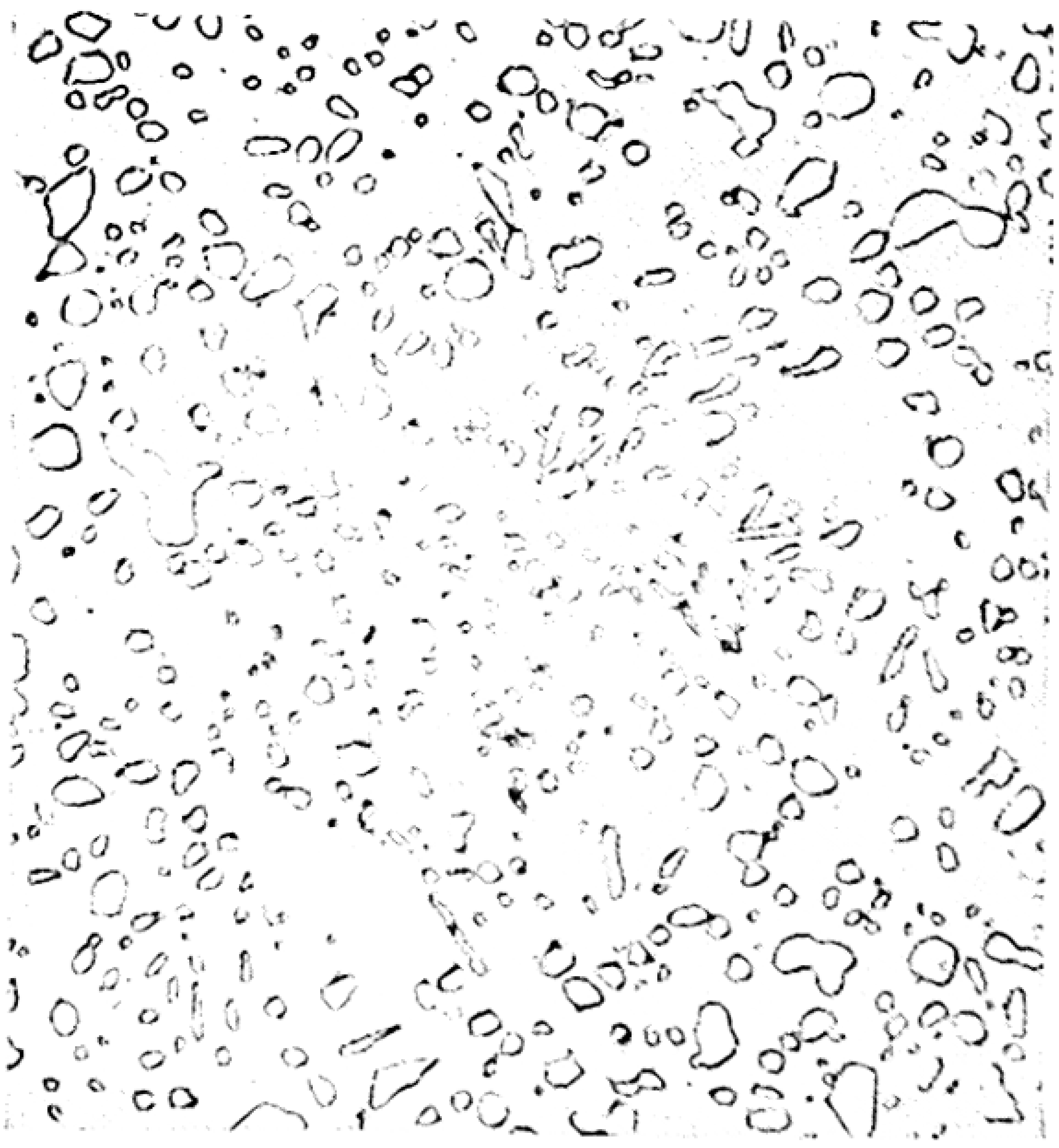


Fig. 7-7. Spheroidized cementite.

Secondary troostite is produced when tempering temperatures between about 400 F and 750 F are employed. It is similar to primary troostite but much easier to make. It is the hardest and the most difficult to machine of the secondary constituents.

Tempering temperatures from 750 F to 1250 F result in secondary sorbite, which has properties similar to primary sorbite except that residual stresses are apt to be smaller. It is more easily machined and softer than troostite.

Spheroidized cementite. When the tempering temperature is just below the line *ABC* in Fig. 7-1, that is, just under 1333 F, the cementite is fluid enough for the small cementite particles of the martensite to coalesce into spherical particles. The particles are spherical because the surface tension makes their areas a minimum. The appearance is that of the spherical cementite particles imbedded in a matrix of ferrite, as shown in Fig. 7-7.

Spheroidized cementite can also be made directly from pearlite. The layers of cementite take a spherical shape when the temperature is just below 1333 F.

Spheroidizing improves the machining qualities, since the hard cementite particles do not approach continuity as in pearlite and martensite.

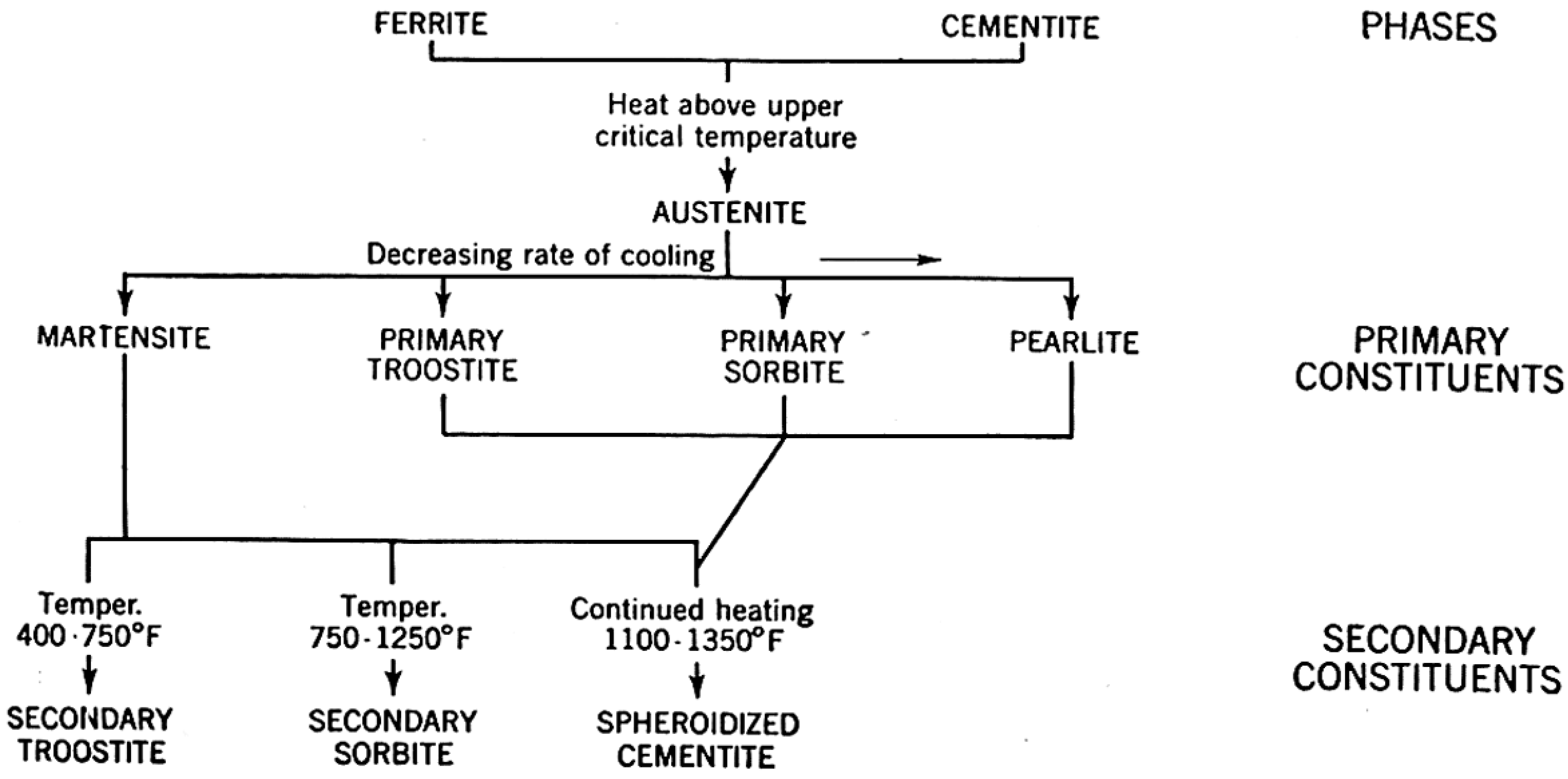


Fig. 7-8. Chart showing relationships between the constituents and phases of steel.

Annealing. Annealing is the heating of steel to about 50 F above the line *DCB* in Fig. 7-1 and then cooling it very slowly in an insulating material such as lime or in a slowly cooled furnace. The main purposes of annealing are:

(1) To refine the grain structure
(2) To relieve internal stresses
(3) To soften for easier machining or working.

Eutectoid or hypoeutectoid steel should be held at the annealing temperature just long enough for the transformation to austenite to be completed. If it is held there longer or if the temperature is too high, the grain size will increase, and the cold-working and machining properties will be impaired. The temperature should be held as low and the time as short as possible. The constituents of fully annealed steel are ferrite and pearlite below the eutectoid, and cementite and pearlite above that composition.

Normalizing. Where large aggregates of constituents or large grains occur, the process of normalizing can be used to make a more homogeneous material and to reduce the grain size.

The steel, particularly in steel castings, is heated some distance above the line *DBE* and held at that temperature until the transformation to austenite is complete. This transformation can be determined only by microscopic inspection. The metal is then cooled in still air at room temperature. If the steel must be held at normalizing temperature a long time in order to break up the aggregates, large grains will form, and the normalizing treatment may have to be followed by annealing. Because of the breaking up of the hard cementite and because of the smaller grains, both high- and low-carbon steels become more machinable after the normalizing operation.

Case-hardening. There are many instances when a hard, wear-resistant surface and a tough, ductile core are desirable in a steel part, such as in cams, gear teeth, pins, and crankshafts. Several processes will produce the hard surface, namely carburizing, nitriding, cyaniding, and surface heating.

In the *carburizing* process (pack-hardening) the low-carbon steel is packed in a carbonaceous material such as coke or graphite and sealed in a box with a small amount of oxygen. The box is then heated to from 1600 F to 1800 F. Carbon is slowly absorbed into the surface, and when the desired penetration has taken place, the part is removed from the packing. The small amount of oxygen in the box acts as a carbon carrier, carrying carbon from the packing to the steel surface. It first combines with the carbon to make CO, which in turn comes in contact with the steel, where the oxygen gives up the carbon and returns for more carbon.

The hardening can be accomplished either by quenching immediately upon removal from the pack or by reheating and quenching. Since the case is high-carbon and the core is low-carbon steel, the case will become hard and the core will remain ductile and shock-resistant upon quenching. The depth of case generally varies from $\frac{1}{32}$ in. to $\frac{3}{32}$ in., since a thinner case may lack a uniform thickness and since there are few applications for a thicker case. Heating periods vary from 6 to 30 hours, depending upon the depth of case specified.

In the *nitriding* process, steel is maintained at temperatures from 900 F to 1100 F in an atmosphere of ammonia gas for periods varying from 20 to 100 hours. If it were not for the excellent results obtained by this process, the time would be excessive. The properties of case-hardness and of wear-resistance surpass those obtainable by any other method. Nitrogen also makes steel so resistant to corrosion that nitrided steel can replace stainless steel in many uses. The tendency to warp is lessened because of the relatively low temperatures, and the depth of penetration is comparable to that obtained by carburization. High-carbon and alloy steels which would harden beyond the case in other methods can be used, since the temperatures are low and no heat-treatment is necessary.

A nitrided case cannot be softened by annealing, but it may be softened with some difficulty by denitriding. Denitriding is done by continued heating at 1800 F or by immersion in a fused bath of potassium chloride and either sodium carbonate or sodium chloride at 1500 F. The heating at 1800 F slowly decomposes the nitrides.

A thin, uniform case of from 0.002 in. to 0.020 in. in depth can be rapidly attained by the *cyaniding* process. The hardening is attained by immersing the steel part in a molten cyanide salt bath at 1600 F to 1800 F, or by first heating the part and then placing the dry salt on the surface to be hardened. By use of the dry salt, the hardening can be localized. Since the formula of the cyanide ion is CN, the process is actually a combination of nitriding and carburizing. Cyaniding has the advantage of rapidity and hardness, but the case is thinner than that obtained by other methods. This disadvantage is not serious in many applications, since the part will be ruined before the case has worn through.

Dispersion-hardening. Dispersion hardening is the formation of hard particles in a soft matrix. Spheroidized cementite is an example of dispersion-hardening, although the greatest use of the process is in making tool bits.

Other methods of surface hardening. Surface hardening can be accomplished by heating and quenching the surface only. This can be accomplished by the use of induction and flame-hardening furnaces, which will be discussed in a later chapter.

Mass effect. The cooling rate in the interior of a large piece of steel is less than that on the case, thus making a softer core. Since a limit exists to the rate at which the steel can transmit heat, no matter how fast the quenching medium is, the cooling rate in the interior is limited.

TTT-curves. In the past few years the TTT-curves (S-curves) have been developed to a point of great usefulness in designing a heat-treatment for a given piece of steel and for a specified result. These curves can be used to establish the heat-treatments of normalizing, annealing, spheroidizing, hardening, martempering, and austempering. The diagram, developed by E. C. Bain and E. S. Davenport, is an isothermal transformation diagram which shows the time, temperature, and transformation relationships.

Figure 7-9 shows a typical TTT-curve for carbon-steel. The ordinates are temperature, and the abscissas are time on a logarithmic scale. Figure 7-9 consists essentially of two curves; the one on the right shows the beginning of austenitic transformation and the other shows the end of austenitic transformation. The horizontal distance between the curves shows the time for isothermal transformation. Each composition of steel must have a diagram.

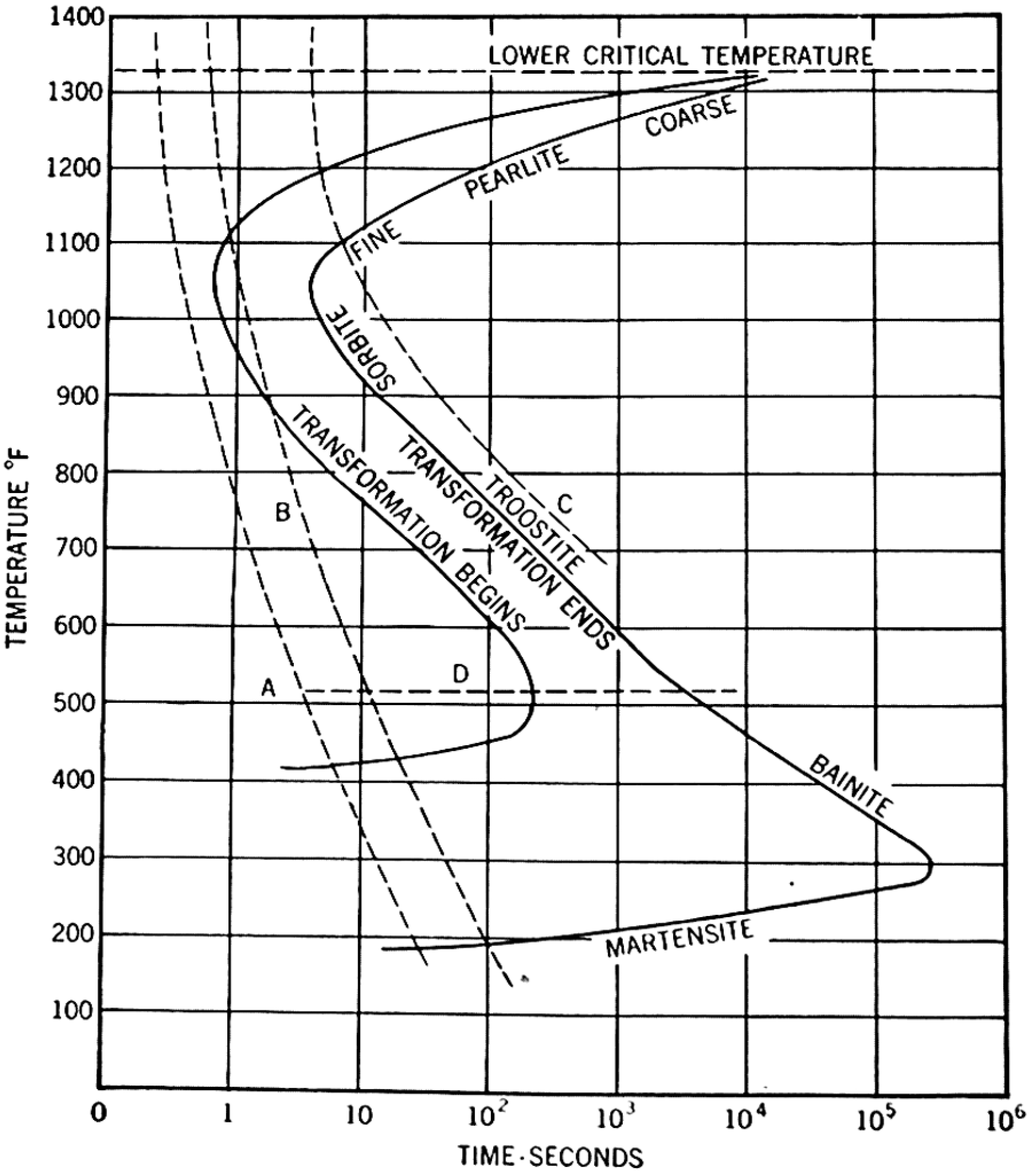


Fig. 7-9. S- or TTT-curve for a typical carbon-steel of about 0.95% carbon content.

The TTT-curve shows clearly what happens when quenching mediums of various cooling rates are used. Assume that the lines *A*, *B*, and *C* represent the time-temperature cooling characteristics of three different quenching mediums. Curve *A* reaches low temperatures so fast that it does not touch the beginning transformation curve until about 425 F. The transformation then begins at that point and continues for about 8 seconds until it is 100% martensite.

Curve *B* represents a slower quench, one slow enough so that transformation starts to take place at 1110 F. At about 890 F, transformation stops. About 30% of the steel has by then become sorbite (very fine pearlite). From that point, cooling without transformation continues to a temperature of about 430 F. The transformation then continues for about 80 seconds until the remaining 70% has become martensite. The cool steel would be 30% sorbite and 70% martensite.

Curve *C* represents a still slower quench, in which the transformation starts at 1210 F after about 8 seconds. It continues for about 15 seconds until a temperature of about 1140 F is reached, where the steel is 100% fine pearlite.

A study of the diagram will show that isothermal quenching can produce grains that ordinarily require hardening and tempering operations. Suppose the cooling of the steel as shown by curve *A* were arrested at about 515 F and maintained at that temperature for some time (curve *D*). After about 120 seconds, transformation would start and continue for some 3000 seconds. The final product would be *bainite*, which has an acicular appearance similar to that of martensite, but it is a much tougher steel. This process is known as *austempering*. Quenching temperatures of 350 F to 400 F are usual for *martempering*, which produces tougher and softer steel than martensite, that is, a tempered martensite.

SUMMARY AND DEFINITIONS

It is necessary to form austenite before heat-treatment can be accomplished. (See Fig. 7-8 for a summary of heat-treatments.)

Martensite is the decomposition product of austenite made by very fast cooling. It has an acicular pattern.

Troostite is a stage between martensite and sorbite having an extremely fine pearlitic structure.

Sorbite is made by using a fairly high tempering temperature. It has a grain structure much like pearlite but finer.

Hypoeutectoid steel is annealed steel having an excess of ferrite and a carbon content less than 0.85%.

Hypereutectoid steel is annealed steel having an excess of cementite and a carbon content greater than 0.85%.

Primary constituents are various decomposition products of austenite.

Secondary constituents are the various tempering products of martensite.

Spheroidized cementite is spherical cementite particles imbedded in a matrix of ferrite. It is made by prolonged heating just under the lower critical point.

Full annealing is the heating of iron alloys to just above the upper critical temperature, followed by very slow cooling. Its purposes are:

(1) To relieve internal stresses
(2) To refine grain structure
(3) To soften for easier machining.

Normalizing is the heating of iron alloys above the upper critical temperature and holding them there until they are 100% austenite, followed by a still-air quench at room temperature.

Carburizing is case-hardening by adding carbon to the surface for the purpose of obtaining a harder surface by heat-treatment.

Cyaniding is case-hardening by the absorption of carbon and nitrogen by steel, followed by fast quenching.

Nitriding is case-hardening by the absorption of nitrogen from ammonia gas at elevated temperatures.

Dispersion hardening is the formation of hard particles in a softer matrix.

Mass effect is the effect of mass upon the cooling rate of the interior of a piece of metal.

TTT-curve is a curve showing the relationship between time, temperature, and transformation.

Austempering is the lowering of the temperature of austenite to a point above that where martensite would form. The transformation is allowed to take place isothermally.

Bainite is a product of austempering having an appearance similar to martensite, but it is tougher.

Martempering is isothermal transformation at 350 F to 400 F. A material resembling martensite, but less brittle, is formed.

PROBLEMS

1. Name the solid phases of steel.
2. What are primary and secondary constituents?
3. What are the purposes of annealing?
4. Where is normalizing used?
5. Discuss the merits of carburizing, cyaniding, and nitriding.
6. Describe the effect upon annealed steel of increasing carbon content.
7. What are the general trends in property changes as the tempering temperatures increase?
8. What is the purpose of spheroidizing steel?
9. Describe completely the changes that take place along the line *B* in Fig. 7-9.
10. How may the grain size be enlarged during annealing?

11. How may the completion of the change to austenite be determined?
12. Describe the effect of mass in the heat-treatment of steel.
13. What is meant by isothermal transformation?
14. Name five machine parts using case-hardening.
15. How is bainite formed?
16. Of what practical use is a TTT- or S-curve?

Chapter 8

FERROUS METALS AND ALLOYS

THE RANGES and combinations of the properties of the ferrous metals have been tremendously enhanced by the use of alloying metals. In order to make an intelligent choice of metals, a machine designer must know the general effects of the alloying metals upon iron and steel, and also how to specify the metal he wants.

Steel classifications. There are several methods of classifying steel and steel alloys; each is based upon certain characteristics. Some of these characteristics are chemical composition, physical properties, uses, manufacturing method, grain size, and heat-treatment. In general, several classifications should be used to specify a steel completely.

S.A.E. classification. The chemical composition of steel should be known in order to specify a heat-treatment; the properties of a metal depend upon the percentage of alloys present. The Society of Automotive Engineers has devised a widely accepted classification which indicates the approximate percentages of the major alloys present. An S.A.E. number actually puts limits on more elements than those indicated by the number. These limits can be found in S.A.E. tables in the handbooks. Each digit of the S.A.E. number tells something about the composition. The first digit indicates the major alloys in the steel, and the second digit gives the approximate percentage of the predominant alloy. In some cases where the percentage of the predominant alloy is over 10%, the second and third digits indicate the percentage, but these cases are almost self-evident. The last two or three digits indicate the percentage or "points" of carbon. For example:

S.A.E. 2340 is nickel-steel containing about 3% nickel and 0.40% or .40 points of carbon.

S.A.E. 11660 is tungsten-steel containing about 16% tungsten and 0.60% of carbon.

A.S.T.M. classification. The A.S.T.M. (American Society of Testing Materials) classification classifies by physical properties. Each class is given a number, by which the tensile strength, the yield point, the percentage elongation, and the limits on phosphorous and sulphur are specified. This classification may be found in the A.S.T.M. Standards.

Other classifications. Many times steel is classified by the manufacturing method, such as open-hearth steel, electric steel, or crucible steel.

The A.S.T.M. has constructed an arbitrary set of standards for specifying grain size. These standards can be found in the A.S.T.M. Standards.

Steels are often classified by uses, such as structural steel, tool steel, and machine steel.

Carbon-steels. Carbon-steel is one of the most versatile of all alloys. Its properties can be varied by changing any one of the following factors:

(1) Carbon content
(2) Heat-treatment
(3) Amount of impurities
(4) Mechanical treatment.

Since each of the factors has a large effect upon the properties, all factors should be closely controlled. The properties of a given steel can be determined by test, by manufacturer's data, or by use of the handbooks.

The following is a tabulation of approximate ranges of some properties of carbon-steel:

Tensile strength	42,000 to 280,000 psi
Elongation	0 to 35%
Brinell hardness	80 to 490
Endurance limit	30,000 to 110,000 psi
Modulus of elasticity	30,000,000 psi for all steels
Modulus of rigidity	12,000,000 psi for all steels

Alloy steels. Alloy steels are steels whose properties are affected by the addition of elements other than carbon. They derive their names from the alloying elements. Thus if the alloying element is nickel, the steel is called a nickel-steel. If one element besides carbon is added, the alloy is classed as a *ternary* alloy; if two are added, it would be a *quaternary* alloy. The following is a list of the more important steel alloys:

Ternary Alloys	*Quaternary Alloys*
Nickel	Chrome-nickel
Silicon	Chrome-vanadium
Manganese	Chrome-molybdenum

Ternary Alloys
Chromium
Vanadium
Molybdenum
Tungsten
Copper

Quaternary Alloys
Chrome-tungsten
Chrome-silicon
Manganese-silicon
Aluminum-chromium

Effects of alloying. The alloying elements may act in several ways:

(1) Accelerate or retard transformations.

(2) Form constituents or compounds that give the elements special properties.

(3) Act as scavengers.

It is useful and instructive to classify the alloying elements according to their effects upon steel. Such a classification follows:

(1) Elements that strengthen ferrite:
Nickel
Manganese
Silicon
Chromium
Aluminum
Cobalt

(2) Elements that form carbides:
Molybdenum
Chromium
Vanadium
Tungsten
Manganese

(3) Elements that remove oxides:
Aluminum
Vanadium
Silicon

(4) Elements that free graphite.
Nickel
Silicon

By using such a classification, it is possible to predict some of the effect of adding an alloying element. Notice that the same element may occur in more than one class.

Nickel. Nickel has several beneficial effects upon steel: it strengthens the ferrite, lowers the critical range, lowers the eutectoid percentage of carbon, and increases the difference between the rising and falling critical temperatures. The lower critical temperatures make it possible to heat-treat at lower temperatures; thus the tendency to crack and to warp is reduced. This effect is increased by the fact that the addition of nickel lowers the percentage of carbon necessary for hardening. Lower-carbon steels have greater ductility and can therefore adjust themselves to uneven stresses more easily. Nickel-steel is stronger and tougher than carbon-steel.

Nickel dissolves in ferrite in all proportions, making it possible to obtain a great variety of alloys. The most common nickel-steels contain from 1% to 5% nickel and 0.2% to 0.50% carbon, but steels containing 25% to 45% nickel are made because of their special properties. The addition of nickel lowers the critical range upon cooling, until at about 25% nickel the critical temperature is below room temperature for all percentages of carbon. Figure 8-1 shows Guillet's diagram, which indicates the influence of the percentage of nickel on various constituents which may be obtained as stable products at room temperature. As the percentage of nickel increases, the critical temperature decreases, until at about 25% it is below room temperature. This influence of nickel makes it possible to obtain austenitic, martensitic, and pearlitic steel without quenching. For example, a 0.7% carbon-steel will have a pearlitic structure on slow cooling between 0% and 6% nickel content. If the nickel content is between 6% and about 14%, the steel will be martensitic; above 14%, it will be austenitic. It is possible to cause a transformation of the austenitic steel by cooling it below room temperature in freezing units.

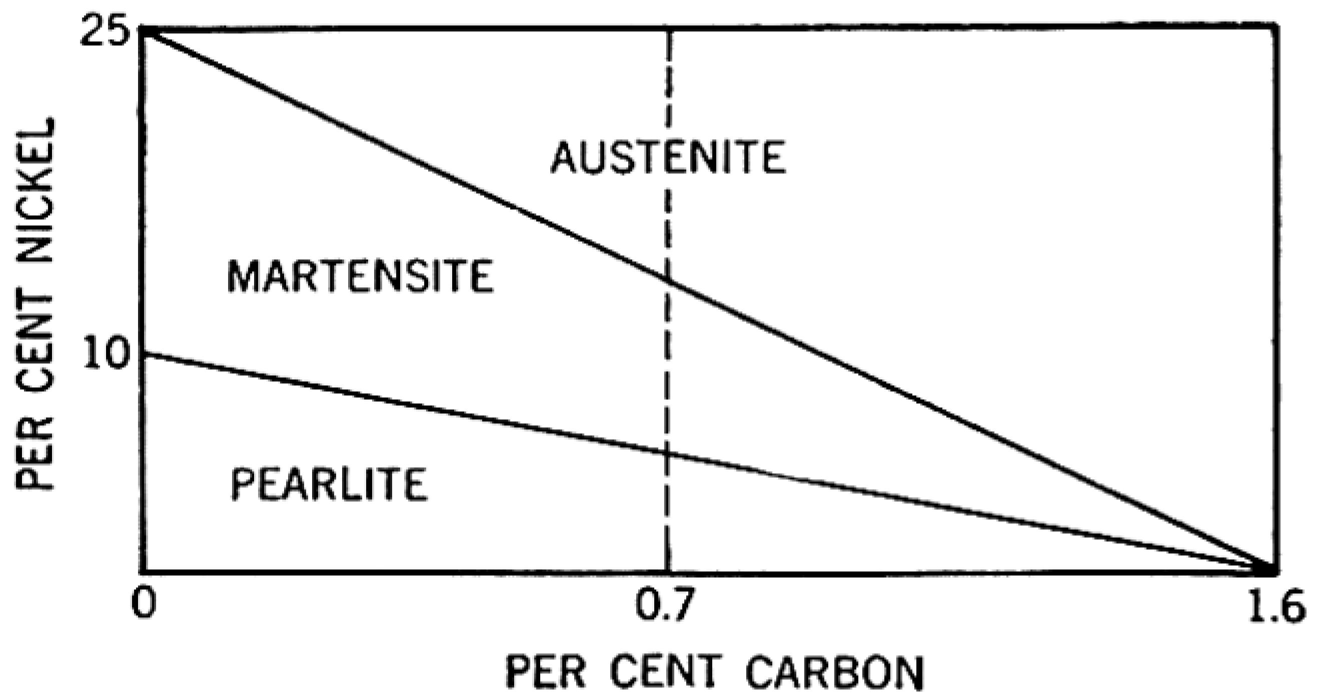


Fig. 8-1. Guillet's diagram showing the influence of the percentage of nickel upon the critical temperature of steel.

Austenitic steels have a high resistance to corrosion and are fairly tough. The martensitic nickel-steels are little used because of their brittleness.

The general properties of nickel-steels are: high tensile strength, hardness, high elastic limit, good ductility, high resistance to corrosion, and low coefficient of heat expansion. Low-nickel steels (0.5% to 5% Ni) are used for structural purposes, armor plate, and automobile crankshafts. The high-nickel steels have a variety of applications because of the low coefficient of expansion and the high resistance to corrosion. *Invar* (36% Ni) is used for the best steel tapes and other length standards, since at that nickel content the coefficient of expansion is practically zero within normal temperatures. *Platinite*, which has a coefficient of heat expansion equal to that of glass, has been used to replace platinum for sealed leads through glass, such as in radio tubes and electric light bulbs. Other applications of high-nickel steel alloys are high-temperature-resistance wire, steel of special magnetic properties, and many more uses.

Nickel-steels can be easily surface-hardened by carburizing and by nitriding.

Chromium. Chromium added to steel strengthens the ferrite, forms extremely hard carbides, and greatly increases the resistance to corrosion. It lowers the cooling critical temperature and raises the heating critical temperature. The solubility of chromium is limited in gamma iron, and chromium-steels harden more deeply than plain carbon-steels. In general, chromium-steel is very hard, has a high tensile strength upon quenching, and an elastic limit near the tensile strength. It has a low ductility, but this makes little difference since the elastic limit is so near the ultimate strength.

Up to 0.5% chromium increases hardenability and toughness, and reduces grain size. It causes deeper hardening because it slows up the transformation process.

From 1% to 2% chromium makes extremely hard, complex carbides which impart the property of great resistance to wear. These steels are used for ball bearings, chisels, high-speed drills, and dies.

Steels containing about 4% chromium and some tungsten and molybdenum are used for high-speed cutting tools. They retain much of their strength at high operating temperatures.

From 4 to 14% chromium gives steel a high resistance to corrosion. It resists even the action of nitric and sulphuric acids and is one form of stainless steel.

Manganese. Manganese resembles nickel since it forms a solid solution with iron and lowers transformation temperatures. Since manganese-steel flows easily, it is used to make sound castings even though the shrinkage is large. The surface of a manganese casting is so hard that it must be ground.

A small amount (0.2% to 0.5%) of manganese is often added to steel to counteract the effect of sulphur. Additions up to 2% may be added to low-carbon steels to improve machinability, ductility, and strength.

From 11% to 14% manganese makes an austenitic steel of great hardness, strength, and toughness. It is therefore used for grinding and crushing machines and for tires on railway wheels.

Tungsten. The most usual tungsten-steels contain from 0.2% to 1.5% carbon and from 3% to 10% tungsten. The tensile strength and elastic limit are high, but the ductility is low. Upon rapid cooling from high temperatures, extremely hard tungsten carbides form. Because of the carbide particles and because tungsten-steel retains its hardness at 1000 F, tungsten-steel makes good cutting tools for extreme feeds. Steel containing 4% to 5% tungsten is used for magnets.

Some austenite is entrapped when tungsten-steel is quenched, but it is unstable at tempering temperatures and changes to martensite on tempering. Tempering therefore increases the hardness in a process called *secondary hardening*.

Tungsten as an element has a tensile strength of about 600,000 psi and a very high melting point. It is useful for electric light filaments. Because of the high melting point, special refining methods are used. The oxide is reduced by hydrogen gas to a powder, which is compressed into two-foot-long bars having a one-inch square cross section. A high electric current is then passed through the bar, causing the temperature to rise to a point where the powder grains will coalesce without melting. The bars are then hammered at about 2800 F to remove the brittleness and to form the desired shape.

Molybdenum. Molybdenum is very similar to tungsten in its effects on steel, although smaller amounts are needed to obtain the same properties. For this reason, it is used to replace tungsten in cutting tools, but some tungsten must be used. It has the disadvantage of having to be heat-treated in a reducing atmosphere, whereas tungsten-steel does not. About 1% of molybdenum replaces 2% to 3% of tungsten, but this gain is somewhat offset by the higher cost.

Up to 1% molybdenum gives steel a high tensile strength and elastic limit with only a slight reduction in ductility. It also reduces creep. From 4% to 9% molybdenum is used in tool steel. Molybdenum is also used in cast iron to reduce the sizes of the graphite flakes, thereby making more continuity in the iron matrix.

Vanadium. Although vanadium has a high cost, it has a more pronounced effect upon steel than any other element except carbon. It helps to remove oxides and forms hard carbides. Only comparatively small amounts of vanadium can be used without producing adverse effects; 0.1% to 0.2% gives the best results. Over 0.3% causes a decrease in tensile strength. From 0.1% to 0.15% increases the tensile strength of low- and medium-carbon steels about 50% with no increase in brittleness. The tensile strength of 0.8% carbon-steel is not changed by the alloying of about 0.2% vanadium, but the elastic limit and ductility are increased. This steel is used for forgings, castings, axles, springs, wrenches, gears, and some instrument work.

Silicon. Silicon strengthens ferrite, removes oxides, and makes free graphite. Small amounts of combined carbon (cementite) cause residual magnetism in steel with the attending losses in electrical machinery. The addition of about 3.5% of silicon to low-carbon steel drives all the carbon out of combination to form free graphite. Silicon increases the tensile strength and elastic limit without decreasing the ductility. Steel containing about 30% silicon resists acids.

Copper. The addition of from 0.01% to 0.30% copper to a steel alloy increases the resistance to corrosion but has little effect otherwise.

Chrome-nickel. Nickel strengthens ferrite; chromium makes carbides; and both reduce the critical temperatures. Therefore, it is possible to get several beneficial effects. Chrome-nickel steels usually contain from 0.30% to 2.0% chromium, from 1% to 4% nickel, and from 0.10% to 0.60% carbon. They have high tensile strength, great toughness, high elastic limit, good wearing qualities, and are easily forged and heat-treated. They show great resistance to fatigue and impact. Chrome-nickel steels may be called the best all-around steel alloy.

Some austenite is entrapped when the metal is quenched. The austenite changes to martensite upon cold-working; as a result, the elastic limit is nearly doubled, and the hardness is greatly increased. The cold-working action of center punching and drilling makes very hard spots in chrome-nickel steels.

Chrome-vanadium. Chrome-vanadium steels are similar to those containing chromium and nickel in their properties and uses. They generally contain from 0.50% to 1.50% chromium, from 0.15% to 0.30% vanadium, and from 0.15% to 1.10% carbon.

Chrome-molybdenum. This steel also is similar to chromium-nickel steels. The usual composition is 1.0% maximum of molybdenum, from 0.50% to 1.5% chromium, and from 0.15% to 1.0% carbon.

Chrome-silicon. These steels have a variety of outstanding properties, depending upon the composition. They may have high resistance to corrosion (particularly at high temperatures), machinability, and hardness. They make good valves for internal combustion engines.

The usual ranges of the alloying elements are from 5.0% to 18.0% chromium, from 1.0% to 4.0% silicon, and from 0.10% to 1.10% carbon.

Aluminum-chromium. The tensile strength of this steel in the annealed state may be 90,000 psi with an elongation of 30%. When the steel is heat-treated, the tensile strength may be as high as 200,000 psi, with an elongation of 11%. Aluminum-chromium steel readily absorbs nitrogen, making a surface hardness as high as 1100 Brinell, compared to 650 maximum for carbon-steel. It is sold as Nitralloy and is used for cams, gages, and bushings.

Cast irons. Cast iron is an iron alloy containing from 3.5% to 4% carbon, with varying amounts of silicon, sulphur, phosphorous, and manganese. Copper, nickel, vanadium, chromium, or aluminum are often added to give special properties.

Cast iron is divided into two classes: white iron and gray iron.

White iron. When all the carbon in cast iron is in the combined form, the metal has a white metallic appearance. It is therefore called white iron. The structure is pearlitic with a large excess of cementite, hence it is very hard and brittle. Almost the only commercial use for white iron is the making of malleable iron. It has a tensile strength of 45,000 psi, a Brinell hardness of 150, and zero elongation.

Gray iron. If a casting cools sufficiently slowly, the silicon in the iron drives some of the carbon out of combination to make flakes of graphite whose diameters vary in size from microscopic to one-eighth inch. The matrix for the graphite becomes pearlite and free ferrite. The strength of gray iron depends upon the condition of the matrix; if it has a large percentage of pearlite and is continuous, it will be strong. The flaky graphite makes gray iron easily machinable. It has a tensile strength of 30,000 psi, a Brinell hardness of 150, and practically zero elongation.

Malleable iron. Malleable iron is white cast iron that has been annealed from 50 to 150 hours. White iron must be used since combined carbon changes to an amorphous carbon during annealing, and forms tiny particles in a continuous matrix. The continuous matrix causes a stronger and tougher material. The properties of malleable iron are similar to those of cast steel, but since white iron pours easily, it makes sounder castings. Malleable iron has a tensile strength of 40,000 psi, a Brinell hardness of 100, and an elongation of 1% to 10%. It is machinable.

Alloy cast irons. The effects of adding nickel or chromium to cast iron depend largely upon the other ingredients present, especially upon the amount of graphite and combined carbon.

Nickel hardens the iron without reducing its machinability. The strength remains about the same, but the grain structure is refined.

Chromium increases the hardness, the resistance to acid corrosion, and the depth chill in chilled sections. Cast iron is chilled to make some parts harder than others. This is done by placing iron in the mold so that heat will be carried away faster at that point. The fast cooling keeps the carbon in the combined form, thus making spots of hard white iron.

A combination of nickel and chromium will produce a machinable casting of high strength and hardness if all the ingredients are closely controlled.

Definitions and Summary

Factors governing the properties of carbon steel:

(1) Carbon content
(2) Heat treatment

(3) Impurities
(4) Mechanical treatment.

Ternary alloy steel is one containing *one* alloy besides carbon.

Quaternary alloy steel is one containing *two* alloys besides carbon.

Alloying elements may act as follows:

(1) May accelerate or retard transformations.

(2) May form constituents or compounds that give the metal special properties.

(3) May act as scavengers.

Secondary hardening is the transformation of entrapped austenite to martensite at tempering temperatures.

PROBLEMS

1. List some bases for classifying steels.
2. Upon what factors do the properties of carbon-steel depend?
3. Discuss and compare white iron, gray iron, and malleable iron.
4. How do alloying elements affect steel?
5. How are alloy steels named?
6. List the effects of several alloying elements upon steel.
7. List some uses for each of the steel alloys mentioned in this chapter.
8. Explain how austenite may be obtained at room temperature.
9. What is secondary hardening?
10. Describe how chilling is obtained and tell the reasons for chilling.

Chapter 9

NON-FERROUS METALS AND ALLOYS

NON-FERROUS METALS have lately become of great importance because research has produced cheaper manufacturing methods and alloys with pronounced properties. Research must still be done to find alloys which will give the best combination of properties for special work. The only metals used extensively as elements are copper, aluminum, and lead.

Hardening of elements. Elements cannot be hardened by heat-treatment as is done in the case of alloys. Hardening by heat-treatment is due to the transformation of solid solutions to other constituents. Such a transformation is impossible in an element since there is no solid solution. Elements can be work- (strain-) hardened by rolling, drawing, or hammering. Work-hardened materials can be softened by annealing.

Copper. Copper, whose specific gravity is 8.94, is used in the pure form for electrical conductors and for special applications requiring corrosion-resistance. It is used as the base for brass, bronze, and several other alloys.

Copper must be extremely pure (99.9%) for electrical purposes, but a lower purity is allowable for castings. Small amounts of impurities greatly increase the electrical resistance. Copper corrodes rapidly and becomes brittle at high temperatures because of absorbed oxygen; at room temperatures a film of oxide forms to shield the remainder of the material.

Hard-drawn copper may have a tensile strength of 68,000 psi, a Brinell hardness of 100, and an elongation of 4%. In the annealed state, the tensile strength could be 33,000 psi, Brinell hardness 50, and the elongation 75%.

Nickel. Nickel is a heavy (sp. gr. 8.7), silvery-white metal which has a high resistance to corrosion. It is made commercially pure for parts needing corrosion-resistance and for plating purposes, but it is most often used as an alloy with steel and copper. Nickel's high resistance to corrosion is due mainly to its high polish.

Zinc. Zinc is a weak, bluish-white metal, with a specific gravity of about 7.1. Commercially pure zinc is used for galvanizing (coating iron and steel) and for die-castings. It is also used as an alloying element in die-casting alloys, brass, and bronze.

The strength of zinc varies from 7,000 psi to 25,000 psi, depending upon the grain size and the amount of strain-hardening. Zinc as an element is susceptible to creep at room temperatures, and the effect increases rapidly for small increases in temperature.

Tin. Tin has a silvery-white appearance and a specific gravity of 6. Its tensile strength may be as high as 4000 psi under direct stress, but it creeps at room temperatures under slowly applied loads. Tin is highly resistant to corrosion and is used as a coating for steel, particularly for canned food containers. It is very ductile and can be rolled into extremely thin sheets known as tin foil. Tin is an important alloy in bronze and bearing metals.

Lead. Lead is one of the heavier commercially used metals, having a specific gravity of 11.33. It is resistant to corrosion by sulphuric acid and is opaque to X-rays. It has a tensile strength of about 2000 psi and it creeps at room temperature at about 500 psi. Structurally, lead is used for pipes, tank linings, weights, and X-ray rooms. It is used in storage batteries and as a base for paints. Lead is added to brass to improve its machining qualities and is used as a base for bearing-metal alloys.

Antimony. This is a hard, brittle metal of low tensile strength which is used in bearing alloys, such as babbit, to give hardness.

Bismuth. Bismuth is a brittle, reddish-white metal which is used in bearing alloys.

Cadmium. Cadmium is a silvery-white, weak, soft metal whose main application is for plating other metals to create resistance to salt-water corrosion.

Chromium. This metal is used to make a hard, corrosion-resistant surface by electroplating. Because of its high polish, it is used for decorative plating on automobile and marine hardware. It can also be used to build up worn parts, such as gages, cutting tools, and pistons.

Magnesium. Magnesium is the lightest of the commercial metals, with a specific gravity of 1.74. Its use has become highly important in the airplane industry in alloy form. Weight for weight it compares very favorably with other metals in strength. It is now being used for bicycles, pruning shears, and wheel-barrows. Magnesium burns very rapidly if sufficient oxygen is present, as in the powder form, so it is used for flares and flash-bulbs.

Aluminum. The popularity of aluminum and its alloys depends upon its light weight (sp. gr. 2.7), resistance to corrosion, strength, and ease of forming. Aluminum shapes can be cut, rolled, forged, drawn, and extruded with considerable ease. It is a good electrical conductor (the best on a weight basis) but it is seldom used because of the necessity for large fittings.

Annealed aluminum has a tensile strength of 14,000 psi, a Brinell hardness of 25, and an elongation of 40%. Work-hardening may double the tensile strength with a great decrease in ductility.

Cobalt. Cobalt is similar to nickel in appearance and properties. From 1% to 12% is used in high-speed steel to make a lasting edge, and it is used in the manufacture of alnico magnets.

Tungsten. Tungsten is a very heavy metal with a specific gravity of 19.3. If properly treated, it is very strong and ductile. Its high melting point (6150 F) makes it ideally suitable for lamp filaments and contact points. About 95% of the tungsten in this country is used in steel for high-speed tools and dies.

Tantalum. Tantalum, like tungsten, is a heavy, high-melting-point metal which is used mainly in alloys for cutting tools.

Non-ferrous alloys. A tremendous number of non-ferrous alloys have been developed for special purposes. These alloys are responsive to various heat-treatments which depend upon the formation and transformation of solid solutions. Many of the non-ferrous alloys have very complicated constitutional diagrams because of the formation of intermetallic compounds. These compounds make a variety of solid solutions. Such diagrams are too complicated for thorough study in this book.

Brass. Basically, brass is an alloy of copper and zinc. Zinc dissolves in copper in both the solid and liquid states. The possibility of forming six different solid solutions exists. Brass containing over 50% zinc is so brittle that it is unusable. Thus only α, β, and a combination of α and β solid solutions are feasible. Alpha brass ranges from 0% to 39% zinc; α and β from 39% to 45.5% zinc; and β brass from 45.5% to 50%.

The α phase has a relatively high tensile strength and is ductile. This brass cannot be hardened except by cold-working and the only heat-treatment is annealing. Annealing at temperatures above the recrystallization temperature (1100 F to 1200 F) relieves residual stresses, and recrystallizes the brass into fine grains which may grow rapidly with time and with increased temperature. It restores the original conditions within the brass.

The strength of brass increases and the ductility decreases as the zinc content increases to about 45%, after which there is a rapid falling off of strength.

Cold-worked brass is subject to *season cracking*. Owing to residual internal stresses, the brass may crack and cause failure at any time without warning, even under no-load conditions. This trouble may be eliminated by a light anneal at between 500 F and 800 F.

The usual brasses contain about 67% copper and 33% zinc. These alloys have good resistance to corrosion, as well as good finish, good casting qualities, and machinability. About 3% lead may be added to make brass more machinable. The strength of brass compares favorably with that of mild steel, but the cost is much higher.

Several special brasses contain other alloys. Aluminum increases the tensile strength and hardness but decreases the ductility. Manganese gives high tensile strength and toughness with ease of casting. The following table gives the constituents of various special brasses and their characteristics:

Name	*Elements*	*Percent*	*Characteristics*
Manganese-bronze	Cu	59	Tensile strength 75,000 psi; ease of casting; resistance to salt-water corrosion
	Zn	39	
	Mn	0.5	
	Fe	0.8	
	Pb	0.7	
Free-cutting brass	Cu	62	Free cutting
	Zn	35	
	Pb	3	
Nickel-silver	Cu	60	Good appearance; corrosion-resistant
	Zn	25	
	Ni	15	
Tobin-bronze	Cu	60	High tensile strength; resistance to salt-water corrosion
	Zn	39.25	
	Sn	0.75	

The bronzes in the above table are not actually bronzes but brasses. An effort has been made to change the names to brass, so at present both names are in use.

The regular brasses are generally broken up into groups having the names: low brass, cartridge brass, and Muntz metal. *Low brass* contains from 1% to 25% zinc and has the appearance of gold. It is therefore used extensively for inexpensive jewelry. Low brass can be hammered and forged easily at room temperatures. *Cartridge brass* contains from about 25% to 38% zinc and it can easily be cold drawn and spun at room temperatures. It is used for tubes, sheets, and special shapes. *Muntz* *metal* contains from 39% to 45% zinc and it may be hot-worked even when it contains large percentages of lead.

Bronze. Bronze is essentially an alloy of copper and tin, but other elements are often added to produce certain properties. Bronzes as a group are harder, stronger, and less ductile than brasses. Because they have high resistance to salt-water corrosion, they are used for marine hardware.

Bronze is an excellent bearing metal. Bearing-bronze structure consists of hard particles in a softer and more plastic matrix. The hard particles provide the wearing quality, and the matrix provides the plasticity necessary for bearings to take the shape of the journal. The matrix may be further softened by the addition of lead. It should be porous to allow oil penetration into the bearing surface.

Bronze has its greatest strength when over 80% copper is used. If less is used, the strength lowers rapidly. The ductility is maximum at 4% tin and practically zero at 25%. The strength and ductility of bronze can be improved by heat-treatment.

Gun-metal bronze, which contains about 90% copper and 10% tin, is the strongest of all bronzes.

Machinery bronze, the hardest of the bronzes, contains from 81% to 87% copper; the remainder is tin.

Phosphor-bronze contains about 89.4% copper, 10.5% tin, and 0.1% phosphorous. It makes a very strong metal with a tensile strength of 105,000 psi. A small amount of phosphorous acts as a deoxidizer, but if any unoxidized phosphorous is left over, it forms hard compounds.

A common type of bronze contains 88% copper, 10% tin, and 2% zinc. It has a tensile strength of 35,000 psi and an elongation of 25%. 10% to 40% lead added to bronze greatly increases its plasticity for bearings.

Silicon-bronze has many of the properties of phosphor-bronze. However, the silicon does not harm the electrical conductivity, as does phosphorous. The silicon is a deoxidizer.

Precipitation-hardening. There are several alloys, such as beryllium-copper and duralumin, which can be hardened by precipitation-hardening (age-hardening). A study of a Case IV equilibrium diagram is necessary for an understanding of this method of hardening. Figure 9-1 shows a typical Case IV diagram. The line CD indicates that a decrease in the solubility of B in α solid solution occurs with a decrease in temperature. This decrease is a necessity for precipitation-hardening.

The process consists of heating an alloy of composition M above the line CD, and holding it there until the equilibrium conditions for that temperature have been attained. The equilibrium condition is a single phase of α solid solution. The metal is then fast-quenched so that there will be no time for *B* to separate out as it again crosses line *CD*. Fast quenching produces an unstable condition at room temperature since *B* is entrapped in a supersaturated α solid solution.

The actual hardening occurs as *B* precipitates out of solution. This sometimes happens slowly at room temperature, but the usual process is to heat the quenched metal to some place below the line *CD*. Since the rate of precipitation affects the properties, the correct aging temperature must be carefully chosen. The hardening is caused by the metal *B* straining the α crystals as it separates, and by the particles of metal *B* preventing movements between boundaries much as sand might do.

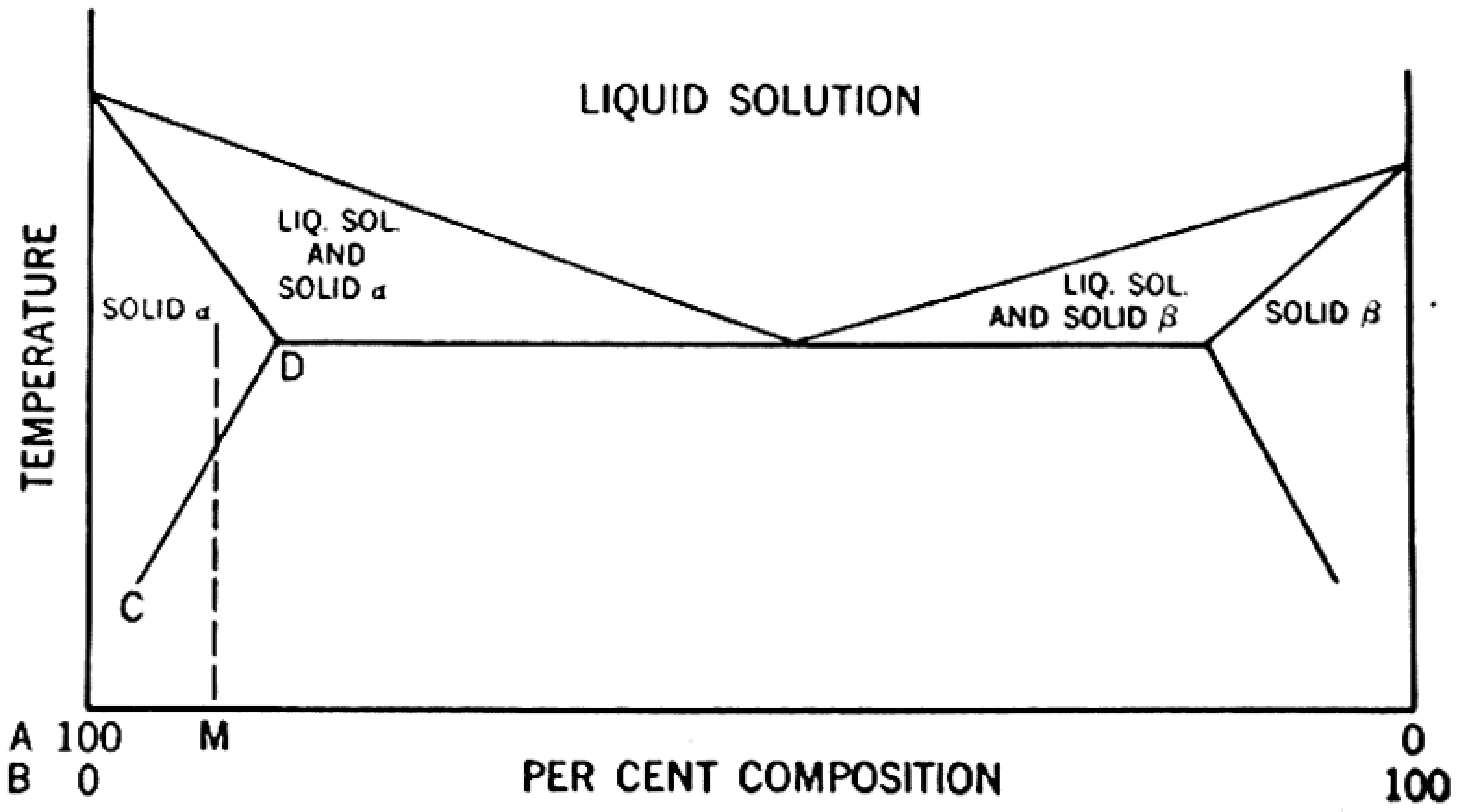


Fig. 9-1. Case IV constitution diagram showing method of precipitation-hardening.

Beryllium-copper. This is a lately developed alloy with many valuable properties. From 1% to 2.25% beryllium is added to copper and, upon precipitation-hardening, the strength increases from 60,000 psi for annealed to 200,000 psi for heat-treated beryllium-copper. Its strength reaches 100,000 psi upon cold-working. It makes excellent springs because they hold their shape indefinitely. Odd-shaped springs can be formed with precision by holding the material in a form during heat-treatment. The spring will not alter its shape after the form is removed.

Aluminum alloys. Aluminum makes a light, strong alloy having a variety of properties which depend upon the alloying metals and the heat-treatment.

The zinc alloy is the cheapest for the benefits derived. Up to 25% zinc can raise the tensile strength from 14,000 psi to nearly 60,000 psi. The metal is easily cast.

The addition of copper up to 8% has somewhat the same effect as zinc, but the alloy with copper has greater ductility. From 5% to 14%

silicon increases corrosion resistance and reduces shrinkage in castings. Consequently this alloy is suitable for intricate castings.

Duralumin. The aluminum alloy containing 4% copper, 0.5% magnesium, 0.5% manganese, and the remainder aluminum, is commonly called duralumin, or 17S. It is the first of the alloys of this type and is still used for general applications. Some modifications are possible which give special properties at the sacrifice of others.

It has become common practice to designate this class of alloys by a number followed by the letter "S." The "S" indicates that it is wrought rather than cast material. A letter which precedes the number indicates that it is a modification of the original alloy. Letters which indicate the temper follow the alloy symbol and are separated from the symbol by a dash, as 17S-T. "T" indicates that the material is cold-worked; "O" that it is annealed; and "RT" that it is heat-treated.

The 17S alloys are heat-treated by heating to a temperature of 930 F to 950 F; they are then quenched in water. The time taken to remove the charge from the furnace and to put it in the water quench should be as short as possible. The quench is followed by aging at room temperature for about four days, or less time at temperatures up to about 390 F. Aging at 212 F requires about 10 hours. The hardening results from the precipitation of $CuAl_2$. The fast quench prevents the separation of the $CuAl_2$ which would occur upon slow cooling. An unstable, supersaturated solution results which will stabilize by the precipitation of $CuAl_2$ if given time. The precipitation can be arrested by cooling to 32 F or below. Duralumin has a Case IV constitution diagram, which was described in Chapter 5.

Rolled duralumin may have a tensile strength of 35,000 psi and an elongation of 4%, and aged duralumin may have a tensile strength of 60,000 psi and an elongation of 20%. Duralumin can be rolled and drawn with considerable ease.

In order to protect the surface of duralumin, it is coated with pure aluminum. The aluminum coating forms alloys with the core and prevents intercrystalline corrosion.

The material is used in structural work requiring lightness, and in airplane parts.

Other aluminum alloys. From 5% to about 15% silicon-aluminum alloys have good pouring qualities. Such alloys are useful for delicate castings. These alloys have good corrosion resistance and a small shrinkage.

Up to about 8% copper hardens and strengthens aluminum as well as increases its fluidity. Copper alloys have a greater ductility than the zinc alloys.

Monel metal. Monel metal is called a *natural metal* since it is made from an ore which already contains the correct percentages of the alloys. It is mined at Sudbury, Ontario. The composition is 67% nickel, 28% copper, and about a 5% mixture of cobalt, iron, and manganese. Monel metal is highly resistant to most corrosive agents, and is used for propellers, sinks, parts of valves, and steam-turbine blades. The tensile strength may be 70,000 psi to 85,000 psi, with an elongation of 30% to 50%. Cold-working may bring the tensile strength to 130,000 psi, with an elongation of 3% to 10%. It is a Case II type of alloy and cannot be heat-treated other than by annealing, since it is a solid solution at room temperature.

Nickel-chromium. An alloy containing 62% nickel, 15% copper, and 23% iron has a melting point of 2462 F and a resistance that makes it highly suitable for resistance-heating units. It is used in electric stoves, flat irons, and many other appliances. If a higher temperature (2550 F) is desired, 80% nickel and 20% copper can be used.

Magnesium alloys. These alloys have extreme lightness and a surprising strength. The aluminum-magnesium alloys are similar to Case III, since they have lines of decreasing solubility at each end of their constitution diagram. Consequently, they can be precipitation-hardened within certain composition ranges.

One of the more useful of the magnesium alloys is *Dowmetal*, which has a composition of 6% aluminum, 3% zinc, under 0.5% manganese, and about 91% magnesium. Castings of this metal are heat-treated by raising the temperature to about 725 F and maintaining that temperature until the solution is in equilibrium. They are then cooled in the furnace by forced draft and are aged at about 350 F. The aging time depends upon the properties to be obtained.

Many other combinations of metals have been devised to make special alloys. Work is being done at the present time on research to find alloys having better properties for the various types of forming, such as drawing and extrusion.

Wrought Dowmetal may have a tensile strength of 42,000 psi and an elongation of 12%. The great advantage of magnesium in airplane construction shows up when the strength on a weight basis is considered. Under this condition, magnesium is nearly twice as strong as some alloy steels and is stronger than duralumin. It is now being used for a great variety of products, such as bicycles, boats, wheelbarrows, and lawnmowers.

Soft metals. *Wood's metal* and *solders* are examples of the large number of low-melting-point metals. Such metals are used for fuses, sprinkler releases, and soldering purposes. The solders generally have a large temperature range during which the metal is mushy in order to make the handling of the solder easier. These metals generally contain some of the following elements: bismuth, cadmium, lead, tin, and antimony. A table of compositions will be found in the Appendix.

These fusable, soft-metal alloys generally have compositions near the eutectic, since that is the lowest melting point.

Bearing metals. Bearing metals should have the following characteristics:

(1) Plasticity, so that the bearing can conform to the shape of the journal.

(2) Low friction, to keep the temperature down.

(3) Ability to accept lubricant, so that it will stay in the bearing.

(4) Good wearing qualities.

(5) Good heat conductivity, to carry the heat away.

(6) High compression strength, so that the bearing will maintain its shape under heavy loads.

Babbitt metal is a tin-base bearing metal having for its composition about 90% tin, 5% antimony, and 5% copper. This metal is plastic and will not crack easily. The metal becomes progressively harder as the percentages of antimony and copper are increased to about 8.5% each. The harder metals wear longer but may crack under pounding. Babbitt bearings are usually steel reinforced. Babbitt should always have more antimony than copper to avoid brittleness. The structure of this metal consists of a tin matrix with hard particles of the inter-metallic compounds of copper-antimony and tin-antimony.

Lead-based bearing metals consist of lead with some hardening elements added. *Bahn metal* is lead with a small percentage of calcium for precipitation hardening. It is a good heavy-duty bearing metal. Other lead-based bearing metals contain about 60% lead; the remainder is antimony and tin.

Zinc alloys. Zinc alloys, except the brasses, are used mainly for die-casting. These alloys have low melting points (about 720 F), a fairly high tensile strength (40,000 psi), and good casting qualities. Consequently, they are suitable for die-casting. A typical composition is 3.5% aluminum, 2.5% copper, and the remainder zinc.

Cutting metals. Cutting materials for high-speed machine tools should have the following characteristics:

(1) Resistance to shock.

(2) High strength at high temperatures.

(3) Particles of extreme hardness.
(4) Maintenance of a sharp cutting edge.

Several materials have been discovered which have almost all these characteristics. The best known non-ferrous alloys are Stellite, cemented tungsten-carbide, and tantalum-carbide.

Stellite is a patented alloy which consists of cobalt, chromium, and tungsten or molybdenum. It holds its strength up to 1500 F, and is somewhat tougher at red heat than when cold. It is brittle, so the cut should be light. It is formed by casting to shape and grinding to size. Cutting speeds 20% to 50% higher than those possible with high-speed steel can be employed.

The elements of *cemented tungsten-carbide* are tungsten, carbon, and cobalt. Since all the melting points of these materials are high, the final product is formed by molding very fine powders under high pressures, followed by sintering in a reducing atmosphere. This process is more thoroughly discussed in the chapter on powder metallurgy. The tungsten-carbide is finally shaped by grinding. A typical composition is 81.4% tungsten, 12.7% cobalt, 5.3% carbon, and the remainder iron. The cobalt content may vary from 5% to 13%, and since cobalt is the bond for the tungsten-carbide particles, the brittleness increases and the resistance to abrasion decreases as the percentage of cobalt increases.

Tungsten-carbide is a very costly material, so small tips are brazed onto steel shanks, sometimes with a shock-absorbing pad of molybdenum between the shank and the tip. The cutting speeds for cemented tungsten-carbide can be several times those of high-speed steels under favorable conditions.

Tantalum-carbide is sintered with iron, cobalt, or nickel as binders. If the bond is nickel, the metal is known as *Ramet*. Tools made of Ramet maintain a sharp cutting edge, can be ground on ordinary grinding wheels, and produce a very fine finish on steel. Because of its cost and brittleness, tips are brazed onto steel shanks.

SUMMARY AND DEFINITIONS

Elements can be hardened only by strain hardening.

Precipitation- or **age-hardening** is the hardening resulting from the precipitation of particles from a supersaturated solid solution at low or room temperatures.

Bearing metals should have the following characteristics:

(1) Plasticity
(2) Low friction

(3) Ability to accept lubricant
(4) Good wearing qualities
(5) Good heat conductivity
(6) High compression strength.

Cutting metals should have the following characteristics:

(1) High resistance to shock
(2) High strength at high temperatures
(3) Particles of extreme hardness
(4) Maintenance of sharp cutting edge.

PROBLEMS

1. State reasons why metallic elements cannot be hardened by heat-treatment. How may they be hardened?
2. Explain precipitation-hardening.
3. What are the main elements in brass, bronze, die-casting metal, monel metal, and Babbitt?
4. What is season cracking and how may it be prevented?
5. What precautions are necessary in heat-treating brass?
6. What is duralumin and what are its most useful properties?
7. What characteristics are desirable in cutting metals? Explain each.
8. What characteristics are desirable in bearing metals?
9. Name the outstanding characteristics of Stellite, cemented tungsten-carbide, and tantalum-carbide.
10. What advantages do magnesium alloys have over others?
11. What characteristics should solder have?
12. Why is lead used in some brass?
13. What property makes copper so important commercially?

Chapter 10

WELDING METALLURGY

WELDING CAN be called a part of metallurgy because of the metallurgical changes that take place in the metal near the weld during cooling. The weld itself may be as strong as the original metal, but the nearby metal may be weakened because of the metallurgical changes during cooling.

Welded joints. Welding processes may be divided into two main groups: *pressure welding* and *non-pressure* or *fusion welding*. Non-pressure welding is accomplished by heating the metal to a molten state, adding sufficient metal to fill the space, and then allowing it to solidify. In pressure welding, pieces of similar material are heated to a plastic state and then forced together under a high pressure. The heat for the melting of the metal can be furnished by oxyacetylene gas, electric arc, or by chemicals, such as Thermit.

Welding metallurgy. Four factors largely determine the final product in any heat-treating operation:

(1) The rate of heating
(2) The maximum temperature
(3) The time at maximum temperature
(4) The rate of cooling.

These same factors must be considered in a study of the effect of welding upon the structure of the metal surrounding a welded joint.

The rate of heating has little effect upon the final structure, although it may cause cracks in a brittle metal if it is too fast. The maximum temperature, the time at that temperature, and the rate of cooling all have a marked effect upon the grain structure and grain size.

Maximum temperature of a weld. The maximum temperature attained in the metal surrounding a weld depends upon these factors: the rate at which heat is applied, the total amount of heat applied, the specific heat of the metal, the mass or thickness of the metal, and the heat conductivity of the metal.

If heat energy is applied very fast, the weld itself heats up before much of the energy can travel to the surrounding metal. A high temperature gradient (temperature difference between two points) with its attendant stresses results, but the grain structure does not change over a large area.

Figure 10-1 is a diagram showing the maximum temperature zones in the metal surrounding a weld of 0.3% carbon-steel. The zones would be closer to the weld if the heat conductivity were less, if the metal were thicker, and if the specific heat were higher.

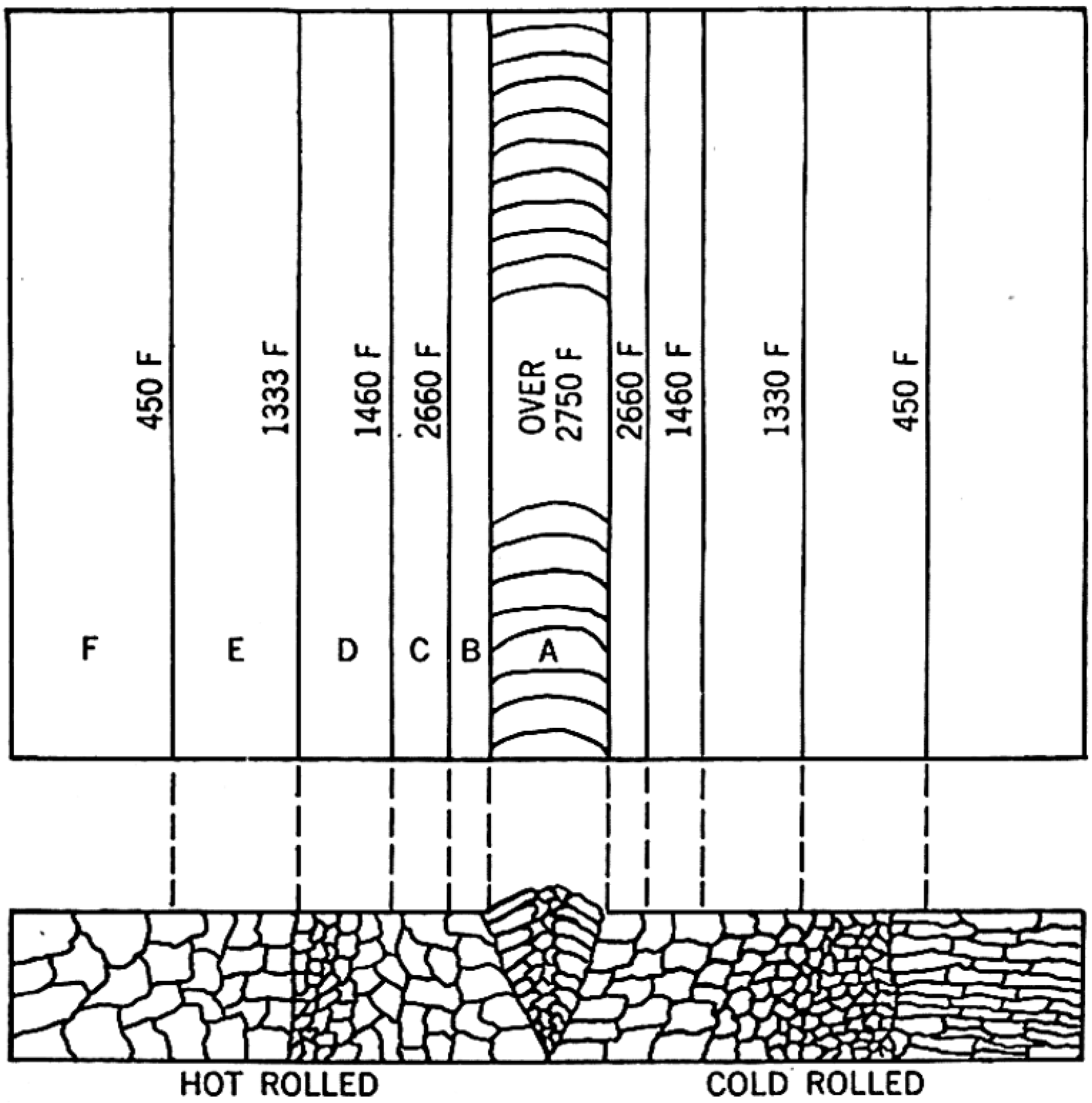


Fig. 10-1. Diagram showing the zones of critical temperatures about a weld of 0.3% carbon-steel and the crystals obtained on cooling in those zones.

The iron-carbon constitution diagram as described in Chapter 6 should be kept in mind as Fig. 10-1 is studied. Zone *A* is above the liquidus, therefore the metal is 100% liquid. In this zone, the liquid may even have boiled on the surface directly under the arc or flame. Between the temperatures 2660 F and 2750 F the metal is in a mushy state and consists of solid austenite crystals in the molten steel. The material in zone *C* is all austenite, with the size of the grains increasing toward the higher temperatures. Zone *D* is varying mixtures of alpha iron in austenite. For hot-rolled steel there is no or little effect below 1333 F, but if the steel has been cold-worked, the strained crystals return to their normal shape, thus weakening the metal.

Effect of cooling the metal. After the flame or arc has passed along, the metal starts to cool. The maximum temperature in the outer zone *F* was so low that there is no change in the grain structure. If the steel were high-carbon and heat-treated, some tempering effects would have resulted. The maximum temperatures in zone *E* would also leave little change in the grain structure on cooling except in the case of strain-hardened material.

Profound changes take place as the metal cools past zone *D*, and it is at this point that the rate of cooling is so important, as is indicated in Chapter 7. The metal transforms from austenite (gamma iron) to alpha iron. Any one of the secondary constituents of steel can result, depending upon the rate of cooling—in other words, the time allowed for the transformation process. The rate of cooling in this zone is high if the temperature gradient is high, that is, if the temperature in zone *E* is low. This statement is based upon the physical fact that the rate of heat-energy flow between two points depends, among other factors, upon the temperature difference between the two points. It now becomes evident that preheating the metal will reduce the temperature gradient and thereby slow the cooling. The rate of heat transfer between two points also depends upon heat conductivity of the metal, since this coefficient indicates the ability of the metal to transmit heat.

Other factors govern the cooling rate. The specific heat and the mass, or thickness, of the metal indicate the ability of the metal in zone *E* to take heat from zone *D* without excessive temperature rise, and they also govern the quantity of heat in zones *A*, *B*, and *C* which must pass through zone *D*. If this quantity of heat is large, the temperature of *D* will tend to remain high and the rate of cooling will be slow. Since heat transfers from one surface to another with difficulty, and since air is a very poor conductor compared to metal, weld areas on thick metals will tend to cool faster than thin metals. This is because the mass of the thin metal is not great enough to absorb the heat. Another factor is the ability of the heat to leave the surface of the metal. If a draft exists, or if the welded piece is in contact with a good conductor, the heat will be carried away faster than in still air.

A study of the TTT-curve for a metal will clearly indicate the importance of the rate of cooling of zone *D*.

Austenite grains grow in zone *C*. The higher the temperature and the longer the time, the larger the grain. This relationship is important since the grain size of the eutectoid in the cooled metal depends upon the grain size of the austenite from which it transforms. Large grains tend to make a less ductile material.

Zone *B* is the mushy stage. In this stage the metal may appear to be solid, but in reality it is a mixture of solid particles in liquid. If stresses are set up about this zone because of contraction of the surrounding metal or because of vibrations, the metal is apt to crack, because metal in this condition has little strength. It must be completely solid before it becomes strong and ductile. This type of failure is called *hot cracks*. The possibility of cracking is increased if steel contains some sulphur. The sulphur forms iron sulphide, which freezes at a much lower temperature than iron or iron carbide. Thus the temperature range during which the metal is in the mushy stage is increased. Steel in this condition is called *red short*.

Zone *A* is in the molten state. Upon cooling, it must go through all the stages with the changes that are dependent upon the rate of cooling. The rate at which crystals grow in this zone can affect the *coring* (composition difference) and *piping* that can take place. The first crystals to form start at the cooler solid walls surrounding the melt and grow inward. Since crystals occupy less space than the molten metal from which they form, a depression or a cavity called *piping* is apt to form at the center of the weld. The first crystals to form in steel are lean in carbon, since carbon reduces the freezing point. If the cooling is slow enough so that crystals start only near the solid metal, the last metal to solidify at the center will be rich in carbon. This action makes what is called *coring*. Should the metal be fast-cooled, crystals will start to grow throughout the molten metal and coring will not have an opportunity to occur.

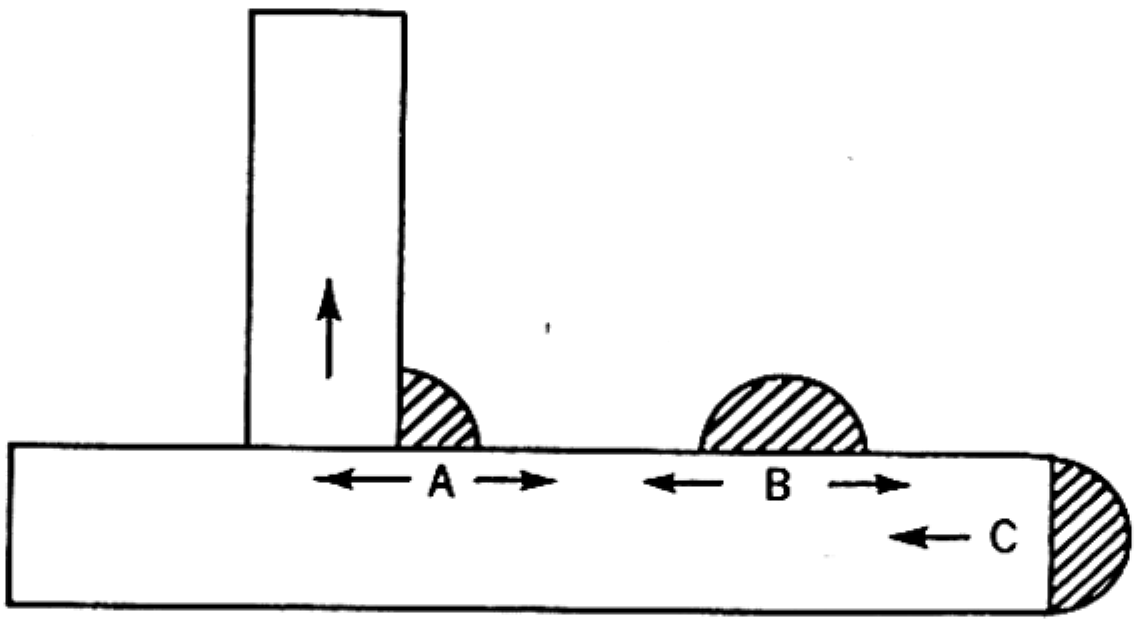


Fig. 10-2. The areas of contact and the possibility of heat conductance of various types of welds.

Figure 10-1 also shows the crystal formation in a cool-welded joint. Although this analysis was based on 0.3% carbon-steel, the same sort of analysis can be made for the weld of any metal.

Effect of the weld position. Figure 10-2 shows welds in various positions. The area of contact for welds *B* and *C* are about the same, but that for *A* is somewhat larger than the others. The effect of this difference would be to cool the weld metal faster in *A* than in *B* and *C*.

The possibility of heat conductance is greatest in *A* because the heat has three directions in which it can travel. It can travel in two directions from *B*, but only one from *C*. In other words, *A* will cool the fastest, and *C* the slowest of the group. The possibility of cracking and coring will be greatest in *A* and least in *C*.

Residual stresses. During the cooling process, stresses may be set up in the metal surrounding the weld. These stresses may at times be nearly as high as the yield strength of the metal. In that case, the load which may be applied before permanent deformation takes place is small. To relieve the stress, the work-piece is annealed.

A second type of residual stress is caused by welding together metals having different cooling curves. Figure 10-3 shows two such metals in various stages of cooling. Suppose that metal *A* has higher critical temperatures than metal *B*, and that both metals are in the plastic state in Fig. 10-3a. Figure 10-3b represents the condition when the temperature has lowered sufficiently for metal *A* to become elastic, but metal *B* is still plastic. In passing through the transformation temperature, *A* shrinks, and since *B* is still plastic and is attached to *A* by the weld, *B* is permanently deformed from the original shape.

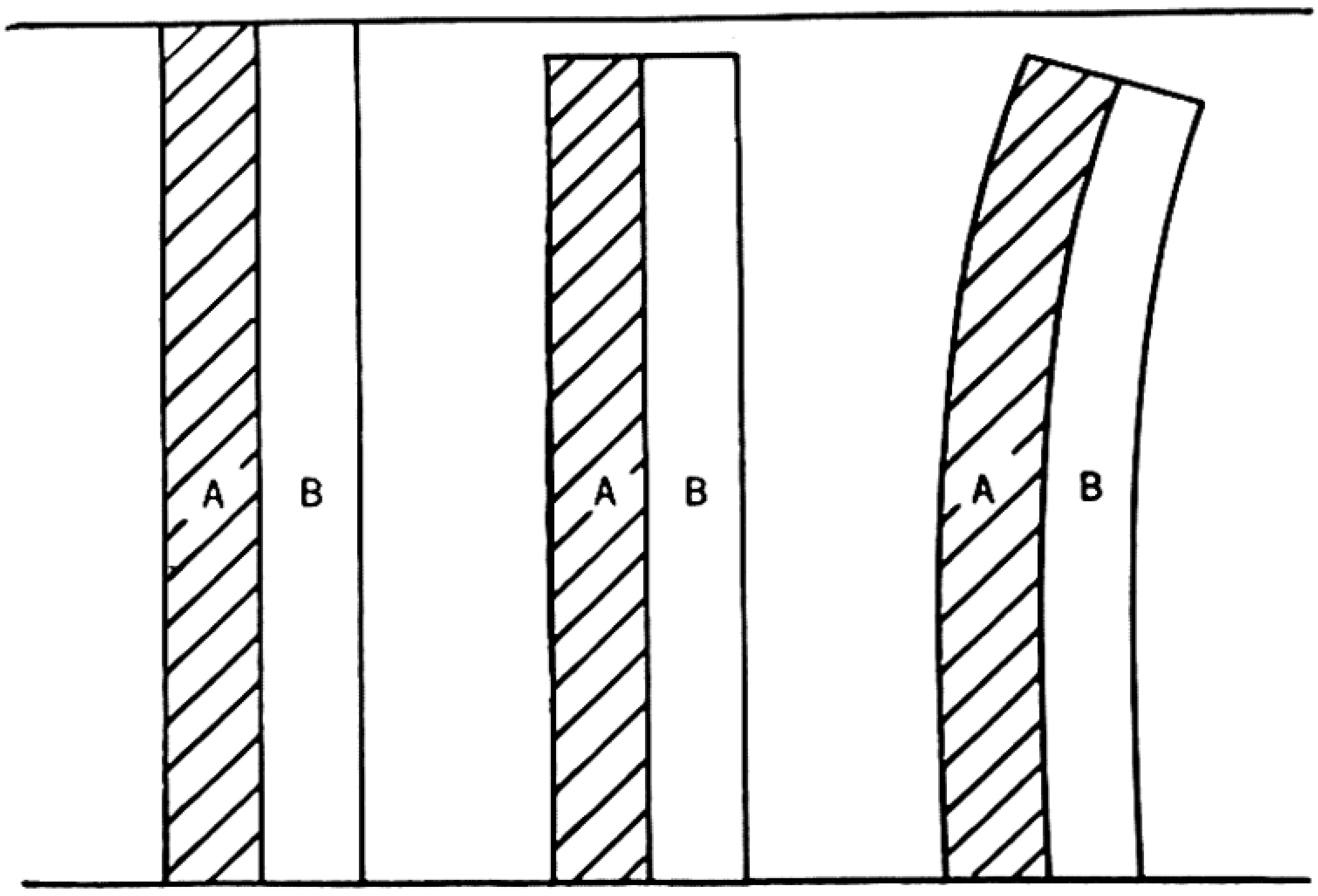


Fig. 10-3. The effect of welding together two metals having different cooling curves.

As the temperature drops through the transformation point of metal *B*, the metal *B* becomes elastic and it shrinks; but it shrinks from the shape it has taken in Fig. 10-3b and not from the original shape. Since metal *A* is in the elastic state, it will not permanently deform, but will shrink according to Hooke's Law. *A* is then in compression and *B* is in tension. Therefore, if the metals are free to bend, they will take the shape shown in Fig. 10-3c. Straightening the metal will increase the stresses.

Effect of peening. The effect of peening varies with the temperature. When the metal is peened while white-hot, the effect is similar to hot-working, which changes the shape easily but has little effect on the grain structure. On the other hand, if the weld is peened while it is at a dull-red heat or just above the transformation temperature, the grain structure will be refined. Below that temperature the effect is that of cold-working, which increases the tensile strength but decreases the ductility. It is difficult to peen at just the right temperature because the operator would have to stop welding at short intervals.

Multiple beads. Thus far only a single pass weld has been discussed. Welds of several beads have a finer grain structure, which makes them more ductile. The second bead heats the previous bead to a temperature just above the critical temperature of 1333 F and holds it there long enough for the steel to become fine-grained austenite. Upon cooling, the grains remain small and the material is ductile. Each succeeding bead refines the previous bead in a multi-bead weld. A conclusion to be drawn from the above discussion would be that several small beads make a better weld than one large bead.

Summary and Definitions

Pressure welding is forcing two pieces of metal together at high pressures while they are in a plastic state.

Non-pressure welding is heating the metal to a molten state, adding sufficient metal to fill the space, and then allowing it to solidify.

The factors which determine the properties of a welded joint are:

(1) The rate of heating
(2) The maximum temperature
(3) The time at the maximum temperature
(4) The rate of cooling.

The maximum temperature depends upon:

(1) The rate of heating
(2) The amount of heat applied
(3) The specific heat of the metal
(4) The heat conductivity of the metal
(5) The mass of the metal.

Hot cracks are cracks which occur while the metal is in the mushy stage.

Red short is a lowering of the temperature of the mushy stage of a metal by an impurity, forming a low-melting-point compound.

Problems

1. What is the difference between segregation and coring?
2. What causes hot cracks?

3. What is red-short metal?
4. Why is multiple bead weld better than a single bead weld?
5. What is the difference between pressure and non-pressure welds?
6. What factors affect the maximum temperature at any point about a weld?
7. What is meant by temperature gradient?
8. What effect does peening have upon a weld?
9. How does the cooling rate affect the structure of the cooled metal?
10. Discuss the effect of the position of the weld upon the cooling rate.
11. How are residual stresses set up and how can they be removed?
12. What is the effect of preheating?

Chapter 11

THE CLEANING AND COATING OF METALS

MANY METALS are contaminated with greases, sand, and oxides after forming and heat-treating operations. Contamination must be removed before coatings or finishes of any type can be applied. In many cases. the cleaning may provide the final finish on the product.

Cleaning metals. The process of cleaning metals can be divided into three general groups: mechanical processes, chemical processes, and electro-cleaning processes. A process is chosen after the metal, the contamination, the finish, and the cost have been considered. This book mentions only a few of the better-known processes.

The mechanical cleaning methods are:

(1) Tumbling
(2) Blasting with grit, shot, or sand
(3) Flame cleaning
(4) Chipping
(5) Brushing
(6) Vapor degreasing
(7) Solvent cleaning
(8) Grinding

Tumbling. Tumbling is used for cleaning small castings, stampings, and forgings weighing under 10 lb. The equipment consists essentially of a horizontal or tilted drum which is rotated by hand or power. The tumbling barrel may be a simple drum or a drum set up for continuous, conveyor-type operation.

The parts to be cleaned are placed in the barrel with an amount of steel balls or specially shaped slugs. As the barrel rotates, the slugs and parts rub and drop on each other. The scale, sand, and rough spots are thus removed or peened flat. The softer non-ferrous metals are sometimes tumbled in sawdust in order that they may be cleaned without having the surfaces damaged.

This is a low-cost method of cleaning castings, since the labor can be unskilled and the equipment is comparatively low-priced.

Blasting. Blasting can be used to clean all types of parts, such as welded parts, castings, forgings, and heat-treated parts. The size of the part is not limited. Sand, scale, and dirt are removed by the force of the high-velocity particles.

Two types of equipment are in general use: those using compressed air at 60 to 100 psi to give the particles velocity, and those using the centrifugal force of rotating wheels to obtain the velocity. The centrifugal type can be used only for heavy shot, but it has the advantage of not being dependent upon a compressed-air supply. The nozzles are generally lined with tungsten-carbide or boron-carbide to provide wearing qualities against the abrasive action of the grit.

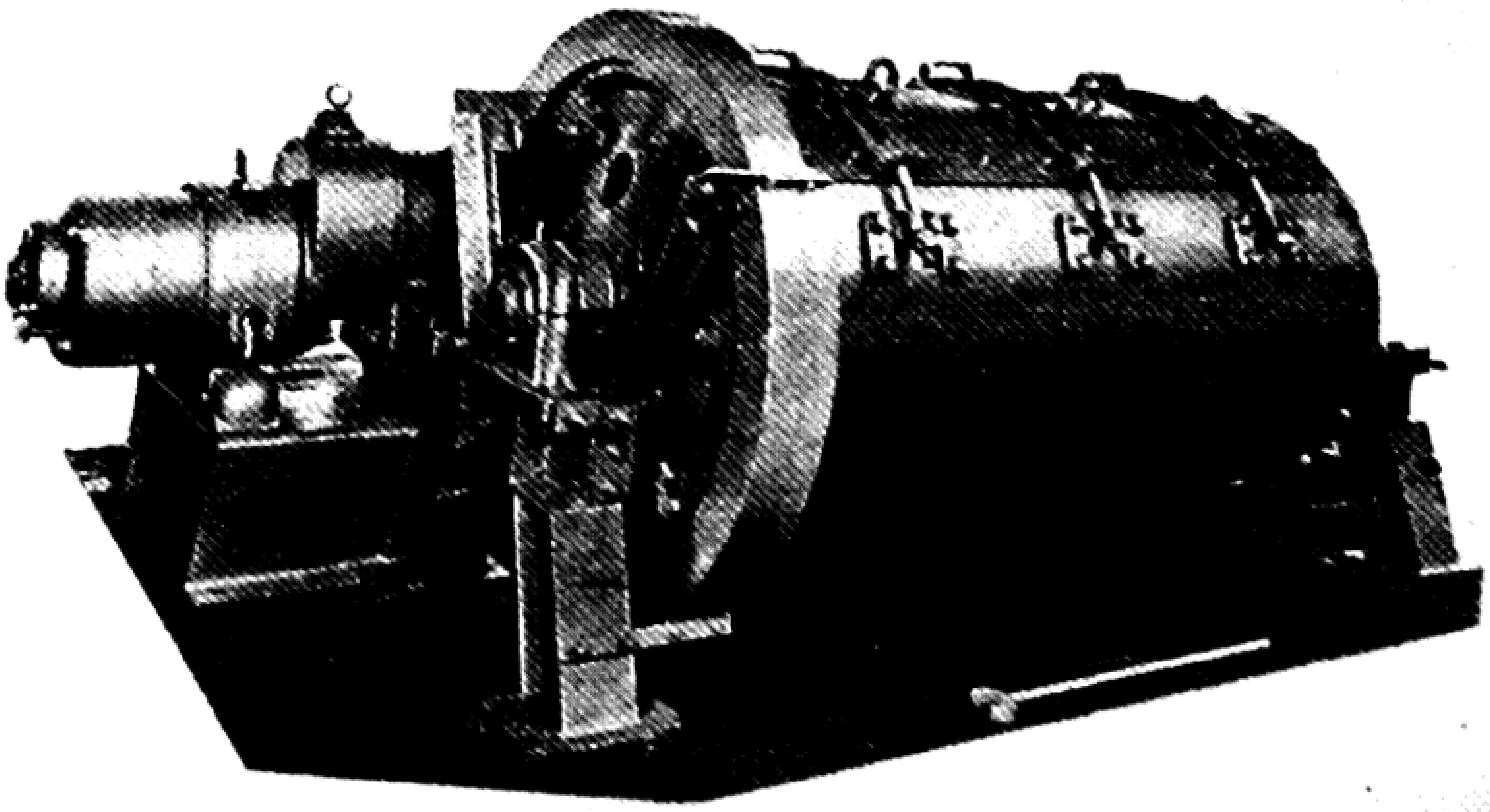


Fig. 11-1. Tumbling mill. *Courtesy W. W. Sly Manufacturing Co.*

The cleaning action and the kind of finish depend upon the size, shape, and material used for the abrasive particles. The metal shot cold-work the surface in a process called *shot-peening*, which improves the fatigue strength of the metal.

An air blast is often used to blow loose or loosely held particles such as sand from castings, and chips from machined parts.

Flame cleaning. Flame cleaning is used on large-work pieces and structural shapes as a preliminary step to painting. It is also used in the steel mill to clean slabs and blooms before the final rolling operations. If the scabs and slivers are not removed, they may be rolled into the surface and spoil the final finish.

The cleaning action consists of heating the surface until the coating of scale and rust flakes and loosens. It is then brushed off, leaving a fairly clean surface. The equipment consists of a multiple-orifice, acetylene-burning torch, and a bottle of compressed acetylene. Since the equipment is portable, it may easily be moved to jobs which otherwise could be cleaned only by chipping or hammering.

Chipping. Chipping is done by tapping the scale with a hammer to break it loose. A chisel is sometimes used. This method is often used on bridges and ships' hulls.

Brushing. Wire brushing is used to clean small parts which can be handled by the operator. It will remove rust, scale, dirt, and scratches, but it cannot be used if the casting is cast to close tolerances because of the wear caused by the wire brush. The brush is a circular wire brush mounted on a high-speed motor-driven spindle. A hood should be provided to collect the dust as it is brushed loose. Care should be taken to avoid uneven stock removal with its consequent spoilage.

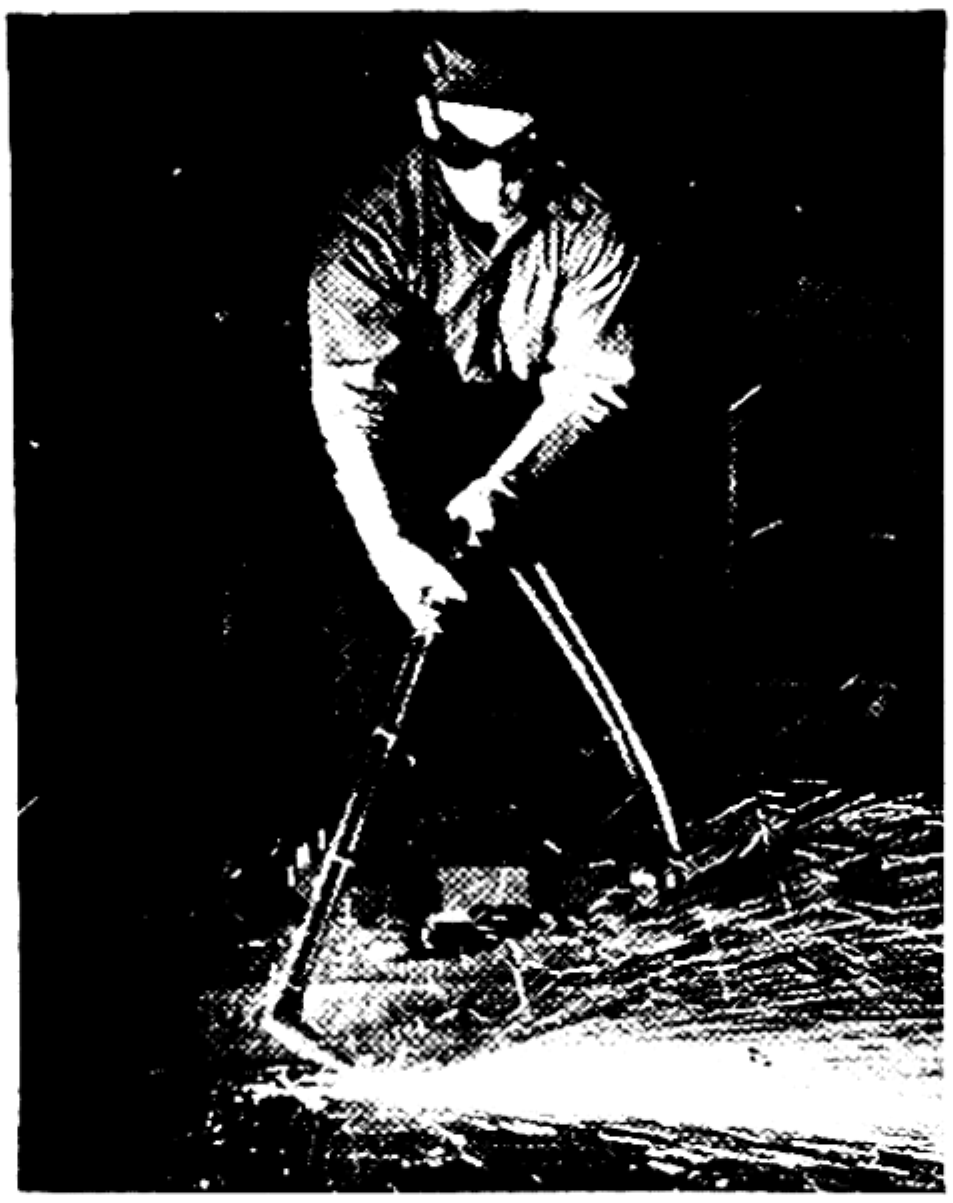


Fig. 11-2. Surface defects are removed by scarfing or burning, preparatory to rolling. *Courtesy Bethlehem Steel Company.*

Vapor degreasing. This method is used on small parts up to about 5 pounds. It consists of a succession of immersions in liquid or vaporized solvents such as carbon tetrachloride or trichlorethylene. The usual sequence of operations is: immersion in boiling liquid, then cold liquid, and lastly hot vapor. These varying temperatures require the use of steam coils and cold-water coils. Hoods are needed to take care of the somewhat toxic fumes.

Vapor degreasing will remove oil, grease, and dirt, but it will leave organic contaminations. An alkaline cleaning operation must be used as a final operation for the removal of organic material if the parts are to be electroplated. Usually the work is dipped into the solvents in baskets. No draining or drying is necessary since the solvents vaporize quickly.

Solvent cleaning. The work parts are dipped in a succession of solvent baths containing petroleum solvents, or the solvents are sprayed on the parts. Since the solvents are generally highly inflammable liquids such as naphtha, gasoline, and Stoddard's Solvent, extra precautions are necessary in this method. A small amount of carbon tetrachloride will reduce the flash point and consequently the fire hazard.

Dirty solvents may be distilled and reused after they become too contaminated for further use. Cleaned parts can be dried by slight heating or by compressed air.

Pickling. Pickling is accomplished by cleaning the metal in an acid bath. The usual acids are sulphuric, nitric, hydrochloric, and ferric sulphate; the choice and concentration of the acid depend upon the metal and the kind of cleaning. Materials for the tanks must be made of some acid-resisting material or must at least be lined with such a material. The lowest-cost tanks are wood or concrete lined with lead, rubber, or asphalt, although lined brick and steel tanks are used. Tanks of monel metal or stainless steel are the most costly.

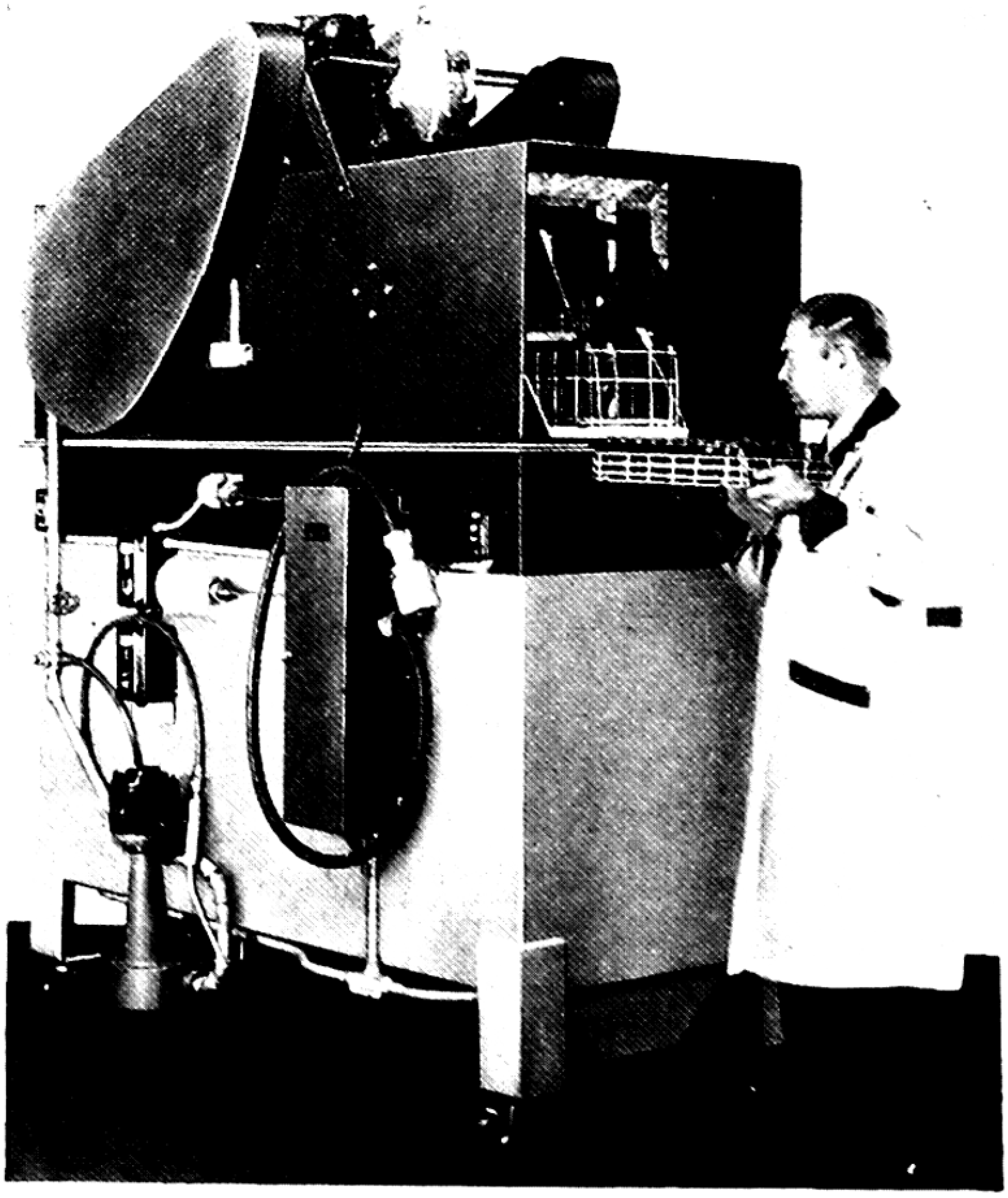


Fig. 11-3. Portable all-electric degreaser using vapor-spray. *Courtesy Phillips Manufacturing Company.*

The cleaning action is much faster if agitation of either the liquid or the parts being cleaned is provided. Agitation of the liquid, which is usually simpler, can be obtained by putting compressed-air jets in the bottom of the tank. In most cleaning baths the action can also be speeded up by heating the fluid with steam coils or electric immersion heaters.

Scales and oxides are removed by this method, and bright finishes may be provided on many non-ferrous metals. Acids will not attack greases and oils, therefore oily parts must first be cleaned in an alkaline cleaner. Disposal of the acids is always a problem. They may be reclaimed or disposed of in the sewers, but if they are drained into the sewers they must first be neutralized.

Alkaline cleaning processes. These processes consist of washing the parts to be cleaned in solutions of such alkalis as lye, sodium hydroxide, or trisodium phosphate. Soaps are often added as wetting agents so that the cleaning solution will come into contact more easily with the surface to be cleaned. These methods are used to remove all types of grease and oil, including slushing oil.

The cleaning may be done by dipping in tanks, by washing in conveyor-type washing machines, or by use of a steam jet. Since agitation and heat greatly speed the process, steam jets are often used in the tanks; or the heat may be supplied by electric immersion heaters, and the agitation by compressed air or by the mechanical motion of the parts. The washing machines usually consist of a series of tanks, containing solutions and rinses, and a conveyor to carry the parts through the cleaning cycle. In many washing machines, the solutions are sprayed on the work-parts; a saving in cleaner thus results, because the concentration can be reduced. Steam jets carry the solution onto large parts which cannot be immersed in a tank.

The alkaline processes are primarily for removing greases and oils.

Electro-cleaning processes. Electro-cleaning is used with both the pickling and the alkaline processes. In this method the work is usually the cathode, and the steel- or metal-lined tank is the anode. The current density for a given voltage depends upon the concentration of the solution. In operation, hydrogen forms on the cathode, where its bubbling action loosens the dirt and scale and then carries them away. The hydrogen also protects the cleaned surface from the action of the solution. Often the tank is equipped with a reversing switch so that the current may be reversed for a few seconds. This action seems to improve the cleaning.

Electro-cleaning requires expensive equipment, but the thoroughness of the cleaning, the saving in time, and the reduction in the loss of metal may more than offset the increased cost.

Cleaning non-ferrous metals. A great many methods and solutions are available for cleaning non-ferrous metals. The choice of a cleaning process depends mainly upon the metal, the contamination, and the final finish. It would be impossible in a book of this scope to discuss all the methods, but the table of methods shown below outlines some of the more common processes.

Coating metals. Metals may be given protective surfaces in many different ways. The type of coating depends largely upon the base metal, the corrosive agent, and the length of time the protection is needed. The following is a partial list of coatings:

- Slushing compounds
- Electroplated coatings
- Tin coatings
- Zinc coatings
- Sprayed metal coatings.

CLEANING NON-FERROUS METAL PARTS

Job	Cycle of Cleaning Operations	Bath Characteristics	Remarks
Wrought and cast Al alloys (except die castings)	1. Soak 3-5 min. in caustic soda solution	2 oz. $NaOH$ per gal. of water	Steel tanks are used for the alkali solutions; also washing machines may be used.
	2. Rinse in cold running water		
	3. Dry		
Sheet Al parts requiring light etching	1. Dip in alkaline solution (trisodium phosphate)	4-6 oz. $Na_3PO_4 \cdot 12H_2O$ per gal. of water at 180-200 F.	If a washing machine is used instead of a still tank, a slightly lower concentration may be used. A light, bright etch is obtained.
	2. Rinse in cold running water		
	3. Dry		
Sheet Al parts requiring heavy etching	1. Soak in alkaline solution	Same bath as above	Acid dip (step 2) removes any smut deposited by soaking in trisodium phosphate. (This smut is not obtained if the work is merely dipped in trisodium phosphate, as above). A heated tank for the alkali and an acid proof tank are both needed.
	2. Dip in nitric acid bath	A 1-to-1 mixture of conc. HNO_3 and water	
	3. Rinse in cold running water		
	4. Dry		
Bright dipping cast Al alloy parts (containing Si, Cu and/or Fe)	1. Immerse in bright dip solution	3 gal. conc. HNO_3, 1 gal. (48 to 52%) HF*	Because of the HF in the bright dip, lead-lined tanks protected with an organic coating are used.
	2. Rinse in cold running water		
	3. Dry		
Pickling wrought Cu and Cu alloys (cartridge brass, leaded brasses, Cu, Ni, Ag, etc.	1. Soak in ferric sulphate solution for ½-4 min.	85 lb. $Fe_2(SO_4)_3$ (anhydrous) per 100 gal. of water at 120-140 F.	The tank for this solution must be acid resistant and capable of being heated. Mechanized or hand dipping equipment may be employed. This treatment will remove scale and stains, and the bath is non-fuming. Economical cleaning is possible over a fairly wide range of bath compositions.
	2. Rinse in cold running water		
	3. Dry		
Pickling Si-Cu and Be-Cu alloys	1. Soak in ferric sulphate-acid bath for ½ to 30 min.	50-170 lb. $Fe_2(SO_4)_3$ per 100 gal. of solution, 32 lb. HF per 100 gal. of solution, at 140-160 F.	Lead, or lead lined, tanks protected by an organic coating are required.
	2. Rinse in cold running water		
	3. Dry		
Bright dip used in conjunction with above pickling treatments	1. Soak in bright dip for ½ to 3 min.	85 lb. $Fe_2(SO_4)_3$ per 100 gal. solution plus one of following: 0.85-8.5 lb. per 100 gal. cream of tartar, 4.2-25 lb. per 100 gal. citric acid or glacial acetic acid	If a high luster as well as a clean surface is needed, this bright dip should follow immediately after one of the above pickling operations, without any intervening rinsing. This is an economical, non-fuming bath and it is not highly corrosive.
	2. Rinse in cold running water		
	3. Dry		
Cleaning brass (removing annealing scale prior to plating)	1. Immerse in red dip (sulphuric acid-sodium dichromate solution) for about 3 min.	8-10% (by vol.) H_2SO_4, 1-8 oz. per gal. $Na_2Cr_2O_7 \cdot 2H_2O$ at 160-200 F.	A lead-lined or ceramic tank that can be heated* is needed. Rinsing operations (especially steps 2 and 4) should be done in two-stage rinses (or a dip followed by a spray rinse). A ceramic, rubber-lined or pure Al tank may be used for the bright dip. This bath should be kept cool; one method of cooling is to use a ceramic tank surrounded by cool running water. For continuous operation this entire cleaning cycle can be mechanized, requiring unskilled labor to load and unload the conveyor or hangers. After final rinsing (step No. 6) the parts should be immersed in plating solution while still wet.
	2. Rinse in cold running water		
	3. Dip in bright dip for 5-30 sec.	1 gal. conc. H_2SO_4, 1 gal. tech. HNO_3, 1 fl. oz conc. HCl, 1 gal. water	
	4. Rinse in cold running water		
	5. Dip in cyanide solution for at least 5 sec.	6-8 oz. $NaCN$ per gal. of water	
	6 Rinse in cold running water		
	(7. Plate)		

Slushing compounds. Slushing compounds are oil- or grease-like materials which can be coated onto a metal surface for protection against the corrosive action of the atmosphere, salt water, or fresh water.

CLEANING NON-FERROUS METAL PARTS—(*Continued*)

Job	Cycle of Cleaning Operations	Bath Characteristics	Remarks
Cleaning Cu and Cu alloy sheet stock (prior to spot and seam welding) and stampings and screw machine parts	1. Wash in solvent		
	2. Soak in hot alkaline cleaner for ½-5 min.	5-8 oz. $NaOH$ per gal. of water at 160-200 F.	
	3. Rinse in hot water		(Sometimes a cold water rinse is used in place of the hot water).
	4. Immerse in bright dip for 5-15 sec.	5 gal. conc. H_2SO_4, 1.5 gal. conc. HNO_3, 3.5 gal. water	
	5. Rinse in cold running water		
	6. Immerse in cyanide solution for 5-10 sec.	6-8 $NaCN$ per gal. of water	The cyanide solution may be warmed (in this case the work is merely dipped in the cyanide solution); an exhaust hood is needed to remove poisonous fumes.
	7. Rinse in cold running water		
	8. Dry[1]		
Electro-cleaning of Cu and Cu alloys	Clean anodically at 20-40 amps. per sq. ft. for ½ to 3 min.	6 to 10 oz. cleaner per gal. of water at 180-200 F.	For removing heavy deposits of dirt, grease, buffing compounds, etc., in a minimum of time the electro-cleaner is used; this may be combined with, or used in place of the alkaline cleaners in the above cleaning cycles.
Cleaning Mg alloy parts	1. Wash in solvent		
	2. Soak in alkaline cleaner solution for 5-15 min.	3 oz. Na_2CO_3, 2 oz. $NaOH$, 1 oz. soap, water to make 1 gal. (solution should be kept boiling)	The efficiency of this cleaning operation is increased if the work is agitated or if a washing machine is used.
	3. Rinse in hot water	140-180 F.	
	4. Rinse in cold running water		
	5. Dry		
Electro-cleaning Mg alloy parts	1. Same as above		The added cost of electrical equipment for this cleaning operation is counterbalanced by reduction in processing time and the use of simpler cleaning equipment (no agitation of cleaner solution or work is needed).
	2. Clean parts cathodically at 10-20 amps. per sq. ft. (at 6 or more volts), 1-3 min.	4 oz. $Na_3PO_4 \cdot 12H_2O$, 4 oz. Na_2CO_3, water to make 1 gal. (solution should be kept as near the boiling point—over 180 F.—as possible)	
	Steps 3, 4 and 5 same as above		
Bright dip for Zn and Zn alloy parts (also for Cd)	1. Immerse in chromic acid solution for 5-20 sec.	30-40 oz. CrO_3 per gal. of solution; 2-4 oz. Na_2SO_4 per gal. of solution	Pure aluminum, or glass-lined or ceramic tanks must be used for chromic acid solutions.
	2. Rinse in cold running water		A two stage rinse (a dip followed by a spray rinse) is good practice.
	3. Dry		
Cleaning Zn alloy die casting prior to electroplating	1. Wash in solvent		
	2. Dip in caustic solution for about 10 sec., or (2. Clean electrolytically in trisodium phosphate solution)	2-5 oz. $NaOH$ per gal. of water at 160-180 F., or (6 oz. $Na_3PO_4 \cdot 12H_2O$ per gal. of water at 170-180 F.)	See section on electro-cleaning.
	3. Rinse in cold running water		
	4. Dip in hydrochloric acid solution	3-5% (by vol.) conc. HC1	Use a lead-lined or ceramic (earthenware) tank for HC1 solution.
	5. Rinse in cold running water		
	(6. Plate)		

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The oils or greases are applied by brushing, dipping, or spraying. Before the coating can be applied, the surface must be cleaned of all possible corrosive agents, since they can cause damage below the grease coating. Slushing compounds can be removed by washing in solvents or in hot soap and water. Certain oils may do double duty as slushing compounds and as lubricants, and therefore need not be removed. Fatty oils and waxes are the usual coatings, although rubber, rosin, or asphalt is often added to obtain a higher viscosity.

The method is used to protect freshly machined parts, auto parts, marine parts, and machines which must be out in the atmosphere.

Electroplating. Electroplating is the electro-deposition of a metal upon the surface of a base metal in order to obtain a desired coating. Metal coatings of this type may be deposited upon steel, copper, brass, nickel, and many other metals. The purposes of such platings may be to:

(1) Protect base metal from corrosion
(2) Produce a desired appearance
(3) Protect base metal from wear
(4) Increase the size of the base metal parts.

In order to specify a plating, standardized specifications have been set up, and tests to check those specifications have been devised. The tests cover protection against corrosion, porosity, hardness, reflecting power of surface, and adherence.

Certain precautions must be observed in the plating process if a good surface is to be expected. The base metal itself should be clean, smooth, and homogeneous. Oils or grease will prevent good adherence of the plating to the base metal; a rough, scratched surface shows through the plating. If the plating does not adhere to inclusions in the base metal, a porous coating is produced. During the plating operation the concentration of the bath, its temperature, the current density, and the anodes must be carefully controlled.

Tinning. Tin plating is a very large industry in the United States. It makes a good-appearing, corrosion-resistant coating which can be used on steel plates.

The general process consists of passing the steel through a flux bath into the molten tin. As the steel leaves the molten tin, it passes between rollers which are submerged in palm oil. These rollers smooth out the tin coating, and the palm oil acts both as a coolant and as a flux which helps distribute the tin evenly.

Tin-plated steel is used in large quantities for food containers and other products, such as roofings.

Zinc coatings. A better-known name for zinc coating is *galvanising*. Zinc-coated steel provides a metal capable of withstanding severe atmospheric and corrosive conditions at a comparatively low cost. It is used for wire, pipes, structural steel, and many other applications.

The usual methods of application are:

(1) *Hot dipping*, where the steel is first pickled in hot sulphuric or

hydrochloric acid, washed, fluxed, dipped in molten zinc, and finally wiped smooth by passing it between rollers.

(2) *Electrogalvanizing*, or zinc plating. As in other electroplating processes, cleanliness of the base metal is of major importance.

(3) *Sherardizing*, where the steel parts are placed in a tumbling barrel with zinc dust. The contents are then heated to about 500 F to 600 F and tumbled until the parts are coated with an alloy of about 10% iron and 90% zinc.

(4) *Spray* or *Schoop process*. See following section on sprayed metal coatings.

Sprayed metal coatings. Any metal which melts in oxyacetylene or oxyhydrogen flames can be sprayed onto other metals or materials. The metal is first melted, then atomized, and finally forced against the base-metal surface.

The most common and simplest type of spray gun consists of a nozzle with three concentric openings. Metal in the form of wire is fed through the central opening at a constant rate. As it comes out of the opening, it passes into the flame, where it is fused and pushed into the compressed-air blast by the force of the flame gases. The compressed-air blast then atomizes the liquid metal and forces it at a high velocity against the base material. Other methods are described in books of larger scope.

SUMMARY AND DEFINITIONS

Some *mechanical cleaning processes* are:

(1) Tumbling
(2) Blasting
(3) Flame cleaning
(4) Chipping
(5) Wire brushing
(6) Vapor degreasing
(7) Solvent cleaning
(8) Grinding.

The *pickling process* removes scale, rust, etc.
The *alkaline process* removes oils and greases.
Some types of coatings are:

(1) Slushing compounds
(2) Electroplated coatings
(3) Tin coatings

(4) Zinc coatings
(5) Sprayed metal coatings.

The purposes of *electroplating* are to:

(1) Protect the base metal
(2) Produce a desired appearance
(3) Protect base metal from wear
(4) Increase size of the base metal parts.

Common methods of *galvanizing:*

(1) Hot dipping
(2) Electroplating
(3) Sherardizing
(4) Spraying or Schoop process.

PROBLEMS

1. Discuss the advantages and disadvantages of tumbling.
2. What precaution must be observed in wire brushing?
3. What are the relative merits of vapor degreasing and solvent cleaning?
4. What type of contamination will pickling remove?
5. What type of contamination will alkaline cleaning remove?
6. What precaution is necessary in the disposal of acids?
7. What is the cleaning action of electro-cleaning?
8. What are several applications for protection with slushing compounds?
9. List the purposes of electroplating.
10. What properties are tested in electroplating?
11. Describe the process of tinning.
12. List and describe the methods of galvanizing steel.
13. How are metals sprayed on a base metal?

Chapter 12

POWDER METALLURGY

Powder metallurgy can be defined as the art of producing a metallic part from powders of a single metal, or of a mixture of metals, or of a mixture of metals and non-metals, by the application of pressure and heat. Modern powder metallurgy started about one hundred years ago with the formation of platinum parts. The furnaces of that time did not produce the necessary high temperatures.

Manufacturing process. Since the powders used in making parts are very fine, a large surface is exposed with a correspondingly large tendency toward oxidation. Since the molecular bond which gives the material strength is produced between clean surfaces, it is necessary to prevent the contaminating oxidation. Consequently, the powders are mixed in a reducing atmosphere wherever possible. When iron powders are used, the air should be kept as free of moisture as possible.

The forming of the part, called *briquetting*, is done by the use of special dies in presses. This step produces a part having only strength enough to hold itself together. The pressures range from 5 to 100 tons per square inch, depending upon the kind of powder and the desired porosity or density. Some investigation concerning the use of repeated pressures is being carried on which seems to indicate that lower pressures can be used to give the same results as the higher, steady pressure. It is evident that the cross-section area of a part is limited by the size of the available presses.

Attempts at reducing the pressures by applying heat and pressure at the same time have been successfully made. The heat makes the powder somewhat plastic and hence more easily compressed. However, the expensive heated dies and the necessity of performing the operation in a reducing or inert atmosphere are decided disadvantages.

Usually automatic devices are connected to the presses for measuring out the correct amount of powder. Automatic machines of the pill-making type can be used for high-speed production, sometimes producing as many as 30 parts per minute. Although the parts made in this type of machine generally have to be small, the results are better because the fast compression seems to reduce the amount of trapped air.

Many limitations exist in the design of dies. The die surfaces must be hard in order to resist the abrasive action of the powder. If the dies become rough, the manufactured part will have a rough surface and ejection of the part from the die will be more difficult.

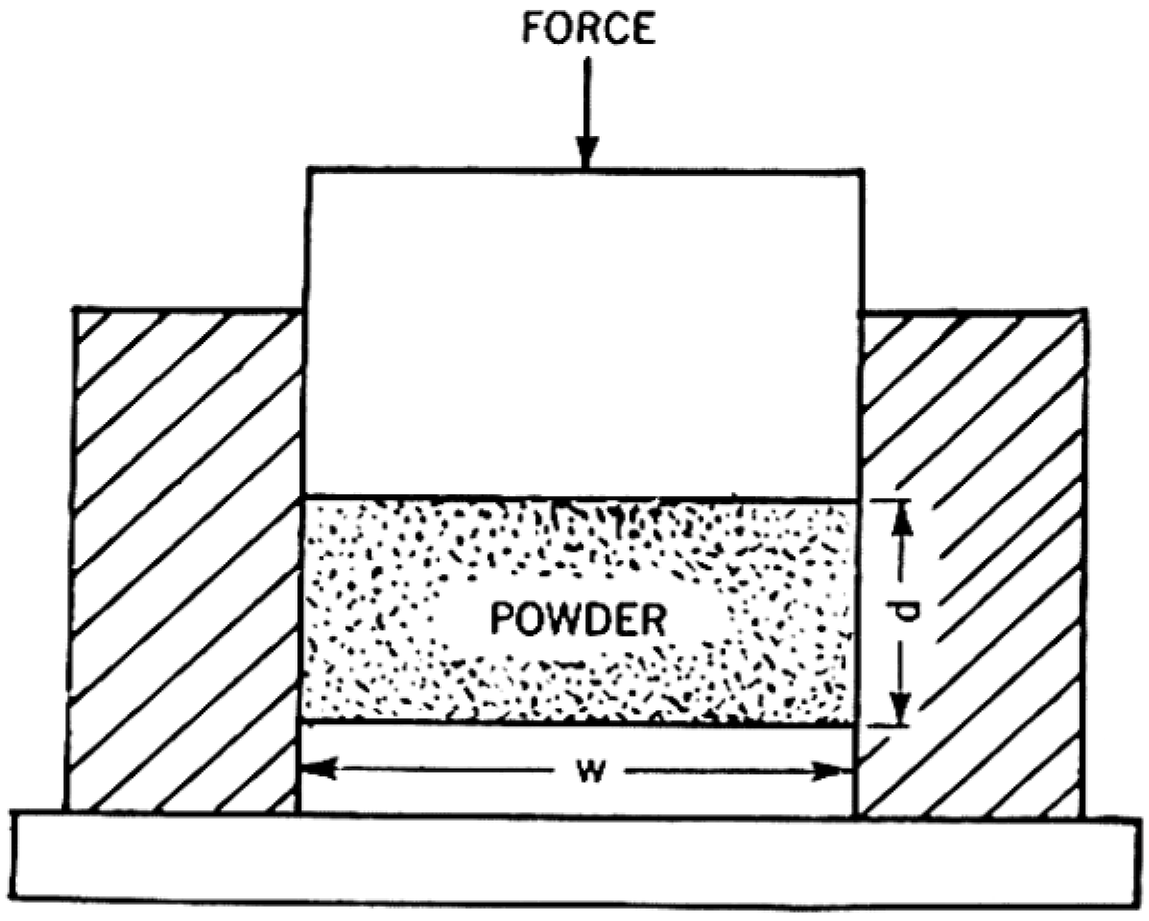


Fig. 12-1. Die showing relationship between depth and diameter.

The ratio of the depth of the die to the width of the top opening must be kept small (Fig. 12-1): that is, *d*/*w* must be small. If it is large, the friction between the powder and the side walls will cause the pressures to vary over the lower cross sections.

Since the powder does not flow freely around corners, re-entrant angles such as shown in Fig. 12-2a cannot be used. If one flange is needed, it should be at the top of the die, as in Fig. 12-2b.

The final step in the making of powdered metal parts is the heat-treating or *sintering* operation. Sintering can be done at the same time as the compression operation, but it usually follows the final forming operation. Since powder metallurgy is nearly always used for quantity production, the furnaces are generally of the continuous-conveyor type. Because of the the large surface area of the small grains, the sintering is done in a reducing or inert atmosphere or in a vacuum. In general, gas furnaces are used; the reducing atmosphere is obtained by using insufficient oxygen, thus filling the furnace with unburned gases. These gases are CO and H_2, which have reducing properties.

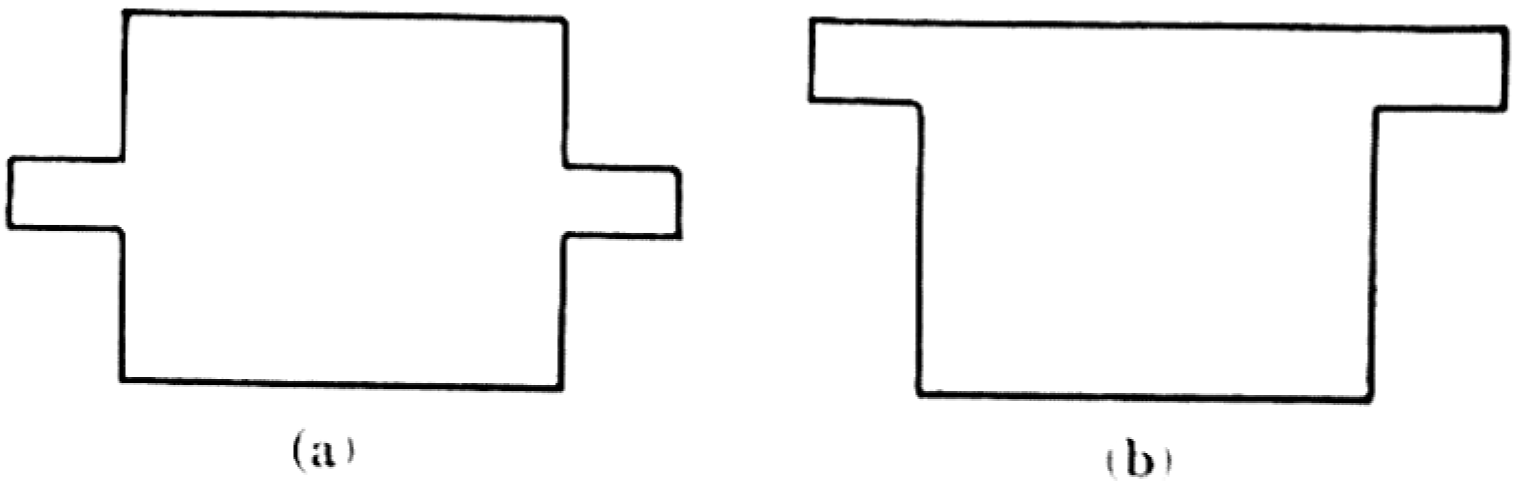

(a) (b)

Fig. 12-2. (a) Re-entrant angle which cannot be made by powder metallurgy. (b) Type of angle or projection which can be made by powder metallurgy methods.

The temperatures used in this step are below the melting point when a pure metal is used, but the lower-melting-point metals may fuse when there is a mixture of powders. Although the metals do not melt, they seem to weld together and to form alloys similar to alloys that have been made from melted mixtures.

Often a porous material is desired for use in making filters and oil-impregnated bearings. For these purposes, the metallic powders are mixed with volatile powders. The volatile powders volatize during sintering, and escape, leaving tiny passages throughout the metal.

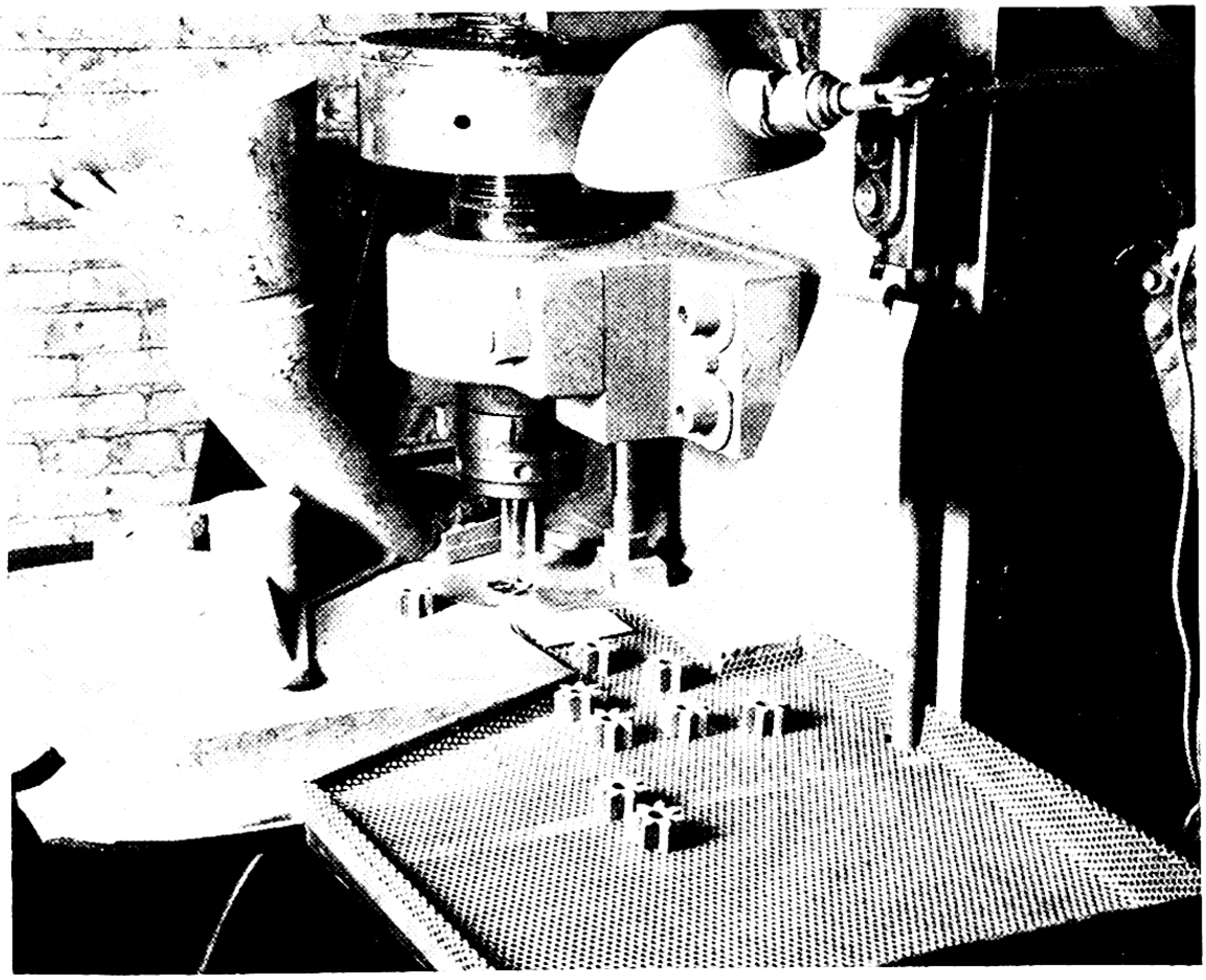


Fig. 12-3. Automatic powder press making gears. *Courtesy Moraine Products Division, General Motors Corp.*

The shape of the powder grains has a great effect upon the physical characteristics of the parts. Angular-shaped grains seem to bind better than globular grains, thus making a harder and stronger material, but globular grains make a more uniformly porous material.

Powders. Although iron, copper, and nickel powders are probably used more than any others, several metals are available in the powdered form. Among them are tungsten, platinum, silver, gold, and cobalt. The sizes of the powder grains available range from 0.006 inches in diameter to the minute carbon grains, which are 1 to 5 microns in diameter.

Powders such as copper, nickel, cobalt, and tungsten are obtained by the reduction of the oxides. The oxides are easily powdered, and, when reduced at temperatures below the melting point, they leave metallic powders. Carbon and hydrogen are generally used as the reducing agents. The size and shape of the grains can sometimes be governed by controlling the rate of flow of the gases over the powder. Electrolytic deposition plus grinding is sometimes used to obtain powders.

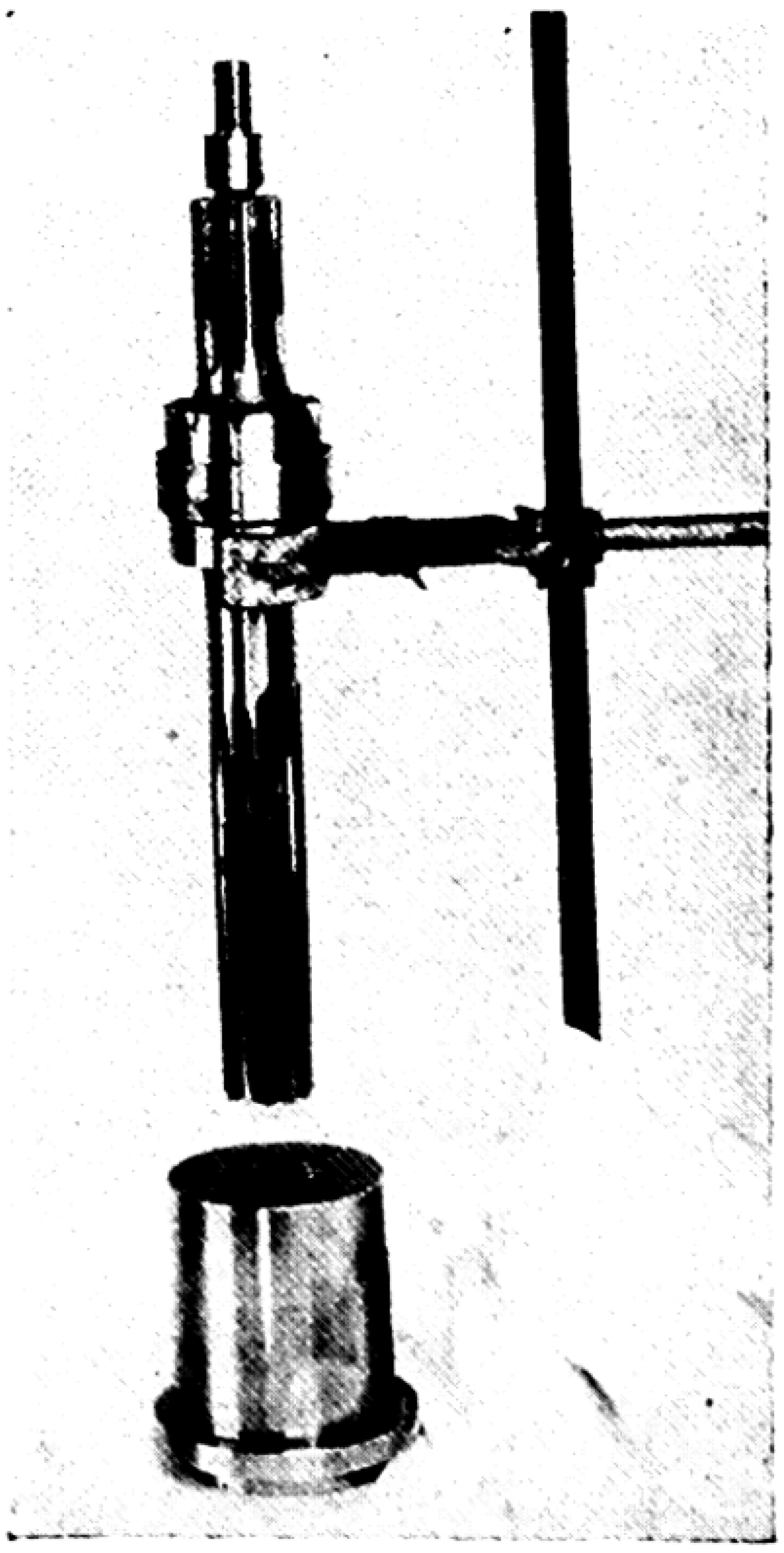


Fig. 12-4. The die "barrel" and punch are fitted to very close tolerances, but permit the air to be forced out under high pressure. *Courtesy Moraine Products Division, General Motors Corp.*

A third method is by atomization, a method similar to that employed in the ordinary fly-sprayer. A stream of molten metal is directed into a blast of compressed air. This action finely divides the metal and at the same time cools it below the freezing point so that it may be collected as a powder.

Precipitation is used to produce the powders of such metals as gold, silver, and platinum.

The larger-grained powders can be sorted according to size by use of a series of sieves. Sieves are as small as 400 mesh: to give an idea of sieve sizes, a 300 mesh means a diameter of 53 microns.

Finer powders, such as the carbide powders, can be measured by determining the amount of light blocked by the powder while in suspension. The carbide powders have diameters from 1 to 5 microns.

Certain physical characteristics of a powder must be known before a machine-press is set up. The density must be known so that the loading ratio can be determined, that is, the ratio between the volumes before and after compression. This ratio indicates the amount of powder that should be put into a die in order to stay within the allowable length tolerances. The rate of flow through various-sized orifices must be known in order that the correct orifice can be chosen for use with automatic machines.

Advantages. Powder metallurgy has many advantages, as well as disadvantages, over other forming methods. The process should not be used as a direct substitute for some other method; rather, a part should be redesigned in order to gain all the advantages of the powder metallurgy process. It is essentially a large-production process because of the high die and press costs.

Parts can be finish-formed to tolerances of 0.001 in. perpendicular to the direction of the pressure, and 0.005 in. parallel to the pressure. The finish is limited only by the smoothness of the die. The smoothness and close tolerances make possible the production of close tolerance and good-finish parts without the cost of further machining.

Very definite advantages derive from the powder metallurgy process if products containing high-melting-point metals, such as tungsten and platinum are to be made. The highest temperature necessary in the process is far below the melting point, therefore lower-temperature furnaces can be used. The cost of furnaces and their operation increases very rapidly as the operating temperatures increase.

Metals that have melting points so far apart that one might vaporize before the other is melted, can be mixed and alloyed by powder metallurgy because of the lower temperatures required in this process. Metals that do not mix when molten, owing to differences in density, as well as metals and non-metals, can be mixed in the powder form and then sintered. Powder mixing is the only way, in many cases, that some materials can be mixed uniformly. By starting with pure powders and by using careful measurements, alloys of exact proportions can be obtained. The effects of the hard-to-eliminate impurities of steel can thus be completely eliminated in this process.

Parts of two separated metals, such as steel-reinforced bearing inserts, can be made by putting the powders in the dies in layers.

Porosity of the metal can be closely controlled and can be varied from 5% to 50% of the volume. The shape and size of the powder grains and the applied pressure are the chief factors affecting the percentage of porosity. Sometimes volatile matter is mixed with the metallic powder. When the volatile matter gasifies during sintering, it leaves the part by forcing its way to the surface, thus leaving holes throughout the metal. The porosity can be varied by the kind and amount of volatile material used.

Many times the increased cost of making parts by powder metallurgy can be more than offset by scrap savings as high as 70% as a result of making the casting in the final form. Further savings can be made by the elimination of machining operations.

One of the greatest advantages is the high-speed production of automatic presses. Production as high as 1800 pieces per hour has been obtained.

Disadvantages. The most obvious disadvantage is the need of large and high-pressure presses and the accompanying limitation in the size of the products that can be formed.

Some powders tend to cling to the vertical walls of the dies. Two bad effects result: defective surface finishes, and a variation in the internal pressures near the bottom of the die.

Because of the large exposed area of the small powder grains, the metal is apt to corrode faster than solid pieces. Since good bonds in the sintering operation are made only between clean surfaces, the air may need to be controlled in the press rooms.

The raw materials have a somewhat higher cost than those for other methods of forming parts, but this high cost may be offset by the savings in machine work and scrap.

Certain limitations in the design exist, such as size and the use of re-entrant angles on the vertical sides of the die. In making parts having concentric circles, such as bearings, some eccentricity is apt to develop which would necessitate machine-work or grinding.

In general, the physical properties of powdered-metal products are lower than those made by rolling or casting. However, this situation can be somewhat offset by increasing the size of the part. Many times certain properties obtainable only by powder metallurgy govern the design.

Applications. The art of powder metallurgy has grown tremendously in the past few years with increased and varied applications. Only a few of the more interesting uses will be mentioned in this book.

One troublesome point that bothers designers of equipment that may be used in both extremely hot and very cold climates is bearing lubrication. In military equipment, especially, lubrication failure is very serious. These troubles have been largely eliminated by the use of oil-impregnated porous bearings. The bearings are first put in a vacuum, then oil is forced into the pores under pressure. The amount of oil that oozes from the bearing depends upon the temperature of the bearing, so that lubrication automatically adjusts itself to the temperature of the bearing. When the bearing cools down after operation, the oil is drawn back into the bearing material. Bearings ranging from the tiniest to some weighing 65 pounds have been made from powdered metals.

High-pressure babbit bearings can be made by first applying a mixture of copper and nickel powders to sheet steel. During sintering, the copper works its way between the grains of the steel backing, leaving a porous nickel layer on the steel. The copper binds the nickel to the steel. The air is then exhausted from the nickel, and babbit is forced into the pores to a depth of about 0.002 inches. This type of bearing has a life of 2 to 5 times that of an ordinary babbit bearing.

The powder metal process is particularly fitted for manufacturing small parts such as door catches, small cams, and hinges. Parts where rubbing occurs, like hinges, can be made self-lubricating, thus eliminating the ever-present squeaky door.

Since tungsten-carbide and diamonds have extremely high melting points, they are difficult to distribute evenly throughout a metal matrix by ordinary processes. Consequently, the making of good cutting tools has been extremely difficult. Powder metallurgy, however, has alleviated this trouble by permitting the cutting powders and the cobalt- or nickel-binding powders to be thoroughly mixed before the forming operation.

Attempts have been made, with some success, at making ribbonless typewriters. The type is made of porous metal impregnated with ink.

Filters capable of withstanding pressures up to 25,000 psi are being made of porous metal. These are particularly adaptable to diesel engine injection systems which operate at very high pressures.

Cast alnico magnets have large grains and are very brittle. The large grain size affects the magnetic properties, and the brittleness affects the machining properties. Thus the number of applications is limited. Small-grained and less brittle magnets can be made by powder metallurgy.

Brake drums which are highly resistant to abrasion can be made by mixing wear-resistant materials with steel while in the powder form.

Small gears are a particularly good application for powder metallurgy, since they can be made in the finished state simply by forming them in a die (Fig. 12-3) and then sintering. They are smoother, cheaper, and quieter than cast gears.

Excellent electrical contacts can be made of tungsten and copper. Under casting conditions, the copper would vaporize before the tungsten melted, but with the lower sintering temperatures it is possible to combine the two metals. The tungsten acts as a porous matrix which can withstand pressures at high temperatures, and the copper provides the electrical conductivity. Even if the temperatures of the contact are above the melting point of copper, the copper is held in place in the porous tungsten by capillary action. This action permits a good spot-welding contact.

Definitions and Summary

Powder metallurgy is the art of producing a metallic part from powders of a single metal, or of a mixture of metals, or of a mixture of metals and non-metals.

The **manufacturing process** consists of compressing the powders in dies at high pressures and heating. The heating may be done at the same time as the compressing operation or as a separate operation after forming.

Sintering is the heating of the formed pieces to temperatures at which the powder grains weld together.

Limitative factors:

1. Die surfaces must be hard.
2. No re-entrant angles may be present.
3. Size is limited by press size.
4. Ratio of depth over width must be small.

PROBLEMS

1. List the advantages of powder metallurgy over other forming methods.

2. List the disadvantages and discuss each fully.

3. What are the major limiting factors in designing parts?

4. What methods are used in obtaining powders?

5. What factors govern porosity?

6. What physical characteristics of the powders should be known by the set-up man?

Chapter 13

FURNACES AND THEIR CONTROLS

An understanding of the operation, characteristics, and controls of heat-treating furnaces is essential for the proper and efficient heat-treatment of metals. Use of the wrong temperature or the wrong type of furnace can spoil many thousands of dollars worth of machined parts.

Desired furnace characteristics. Several general characteristics govern the choice of a furnace other than that of particular application.

Furnaces should have the ability to heat to temperature quickly. This factor can save much inactive time for both the furnace and the operator.

In many heat-treating operations, close control of the furnace temperature is essential for good results. Close control can be accomplished by the use of automatic controls set to narrow variation limits.

Elevated temperatures tend to accelerate chemical reactions. As a result, oxidation becomes a serious consideration in heat-treating operations. The type and effectiveness of the atmosphere control are worthy of serious consideration.

Many furnaces do not heat uniformly throughout the heat-treating chamber, and the thermocouples do not indicate the temperature of the piece being treated. As a result, variations in the properties of different parts of the product may occur. Furnaces should be designed to eliminate these troubles.

Another important factor is the efficiency of the furnace. Is the insulation good enough so that temperatures may be maintained with a minimum input of energy?

A thorough investigation of the general mechanical construction may prevent much lost time due to breakdown of the fire brick or the framework.

Fuels. The most suitable fuels for use in heat-treating furnaces are artificial gas, natural gas, liquified petroleum gas, and oil. Where rigid temperature and atmosphere control is necessary, the gases are the most suitable, but oil heat can be controlled by using the proper care and automatic equipment. The major combustible elements in these fuels are hydrogen and carbon, which make H_2O and CO_2 as products of complete combustion. A check of the flue gases will indicate whether the air-fuel ratio is lean or rich. If it is lean, there will be an excess of oxygen, showing that too much air is entering the combustion chamber; if the mixture is rich, there will be an excess of CO, indicating that all the carbon has not been completely burned.

Types of furnaces. There are a large number of types of furnaces. In some, the parts to be treated may be placed in the heating chamber. In others, the parts may be carried through the furnace on conveyors.

Some of the more common types are:

(1) Open-muffle, fuel-fired furnaces
(2) Semi-muffle, fuel-fired furnaces
(3) Muffle fuel-fired furnaces
(4) Liquid-bath pot furnaces
(5) Electric furnaces
(6) Induction electric furnaces
(7) Flame-hardening furnaces.

Each type of furnace has advantages for special purposes, so all types should be considered when picking a furnace for a job.

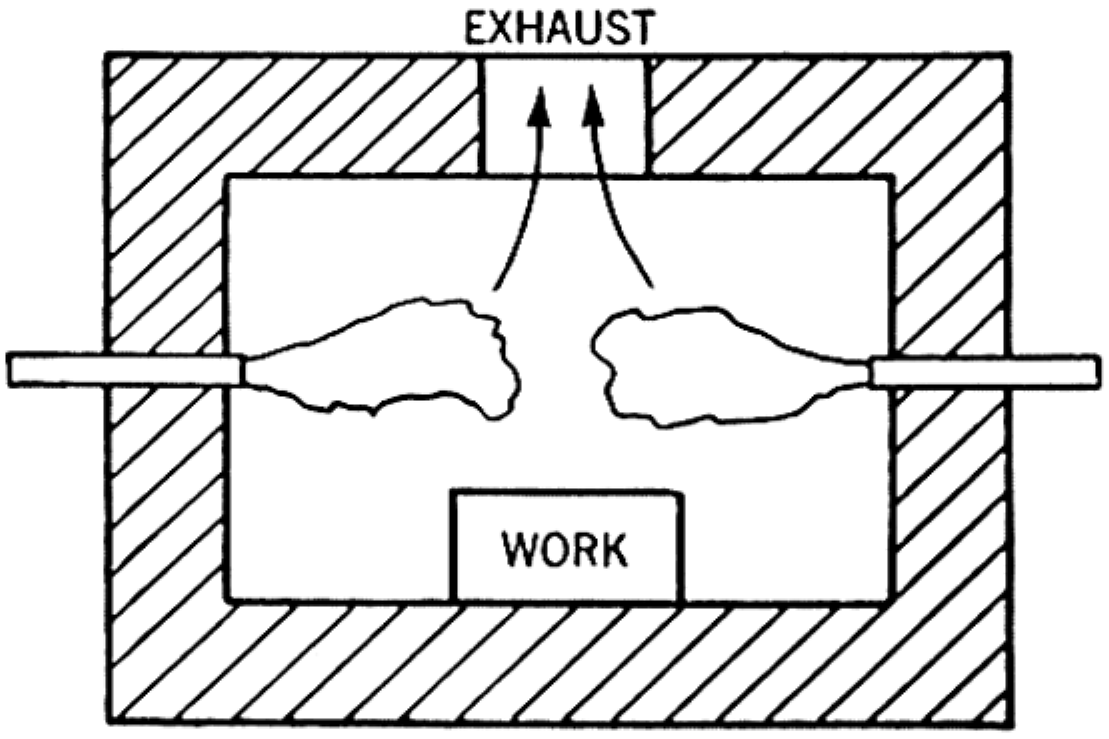


FIG. 13-1. Cross section of open-muffle furnace.

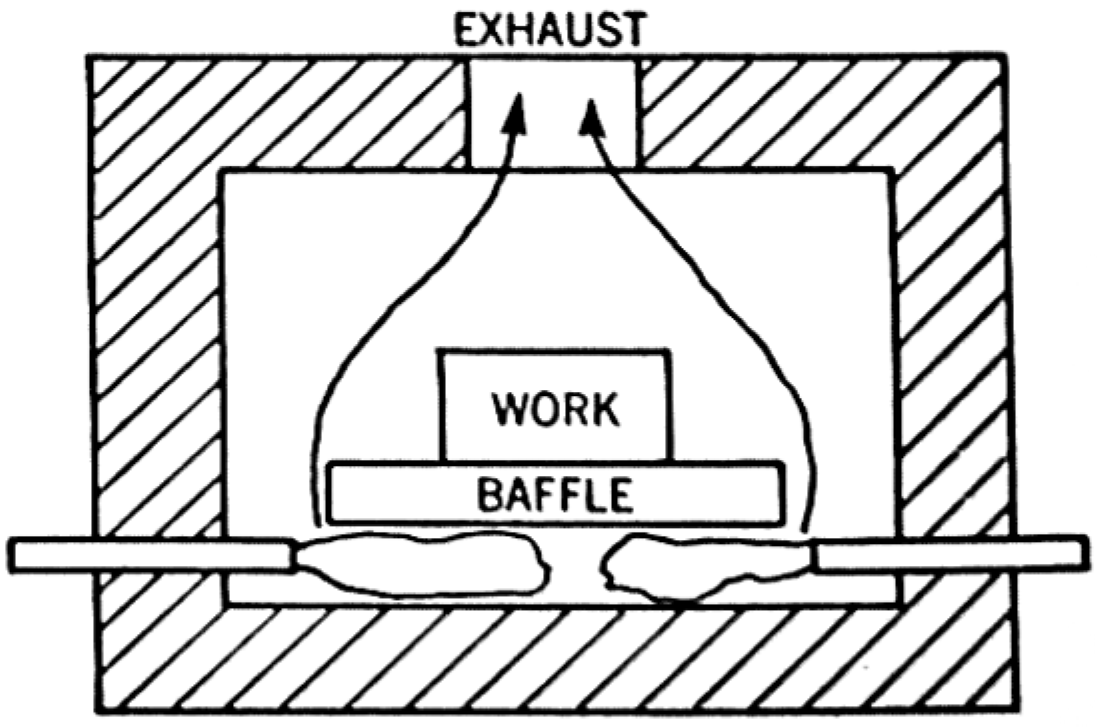


Fig. 13-2. Cross section of semi-muffle furnace.

Fuel-fired furnaces. The combustion in an open-muffle furnace (Fig. 13-1) takes place in the heating chamber, usually above the charge. This type is used for temperatures above 1900 F because of its heating efficiency, but it may have the disadvantages of uneven temperatures and of the possibility of forming scales easily.

Figure 13-2 shows the cross section of a semi-muffle furnace. The combustion chamber is usually below the heating chamber, although it may be above or on the sides. The gases pass through the heating chamber as indicated, but the charge is protected from the flame by a suitable baffle. Semi-muffle furnaces are used for temperatures up to 1900 F. The hot gases may be circulated by fans in order to get more uniform temperatures and to get more heat from the gas. It is more efficient than a muffle furnace because of the more direct heating, but the possibility exists that the exhaust gases will contaminate the charge surfaces and spoil the finish. Also, the furnace atmosphere can be made reducing by enriching the mixture, whereas this arrangement cannot be made in the muffle furnace.

The muffle furnace is shown in Fig. 13-3. In this type none of the products of combustion can come into contact with the charge. This feature leads to the disadvantage of inability to control the heating chamber atmosphere by control of the air-fuel ratio, but it does make possible outside atmosphere control.

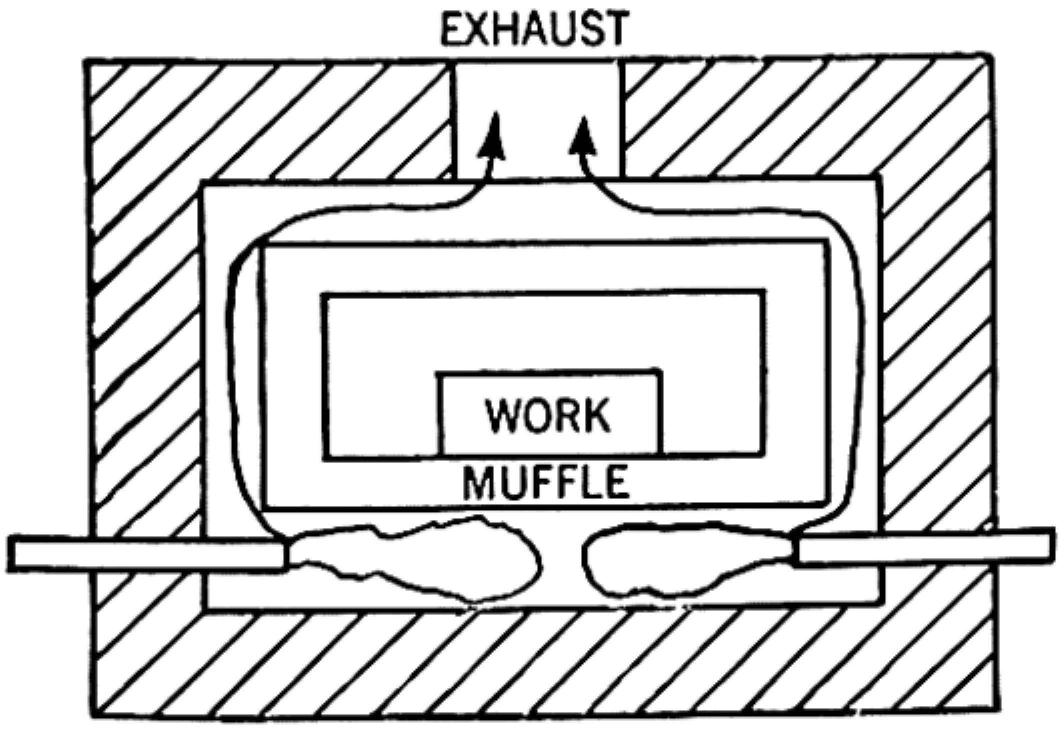


FIG. 13-3. Cross section of muffle furnace.

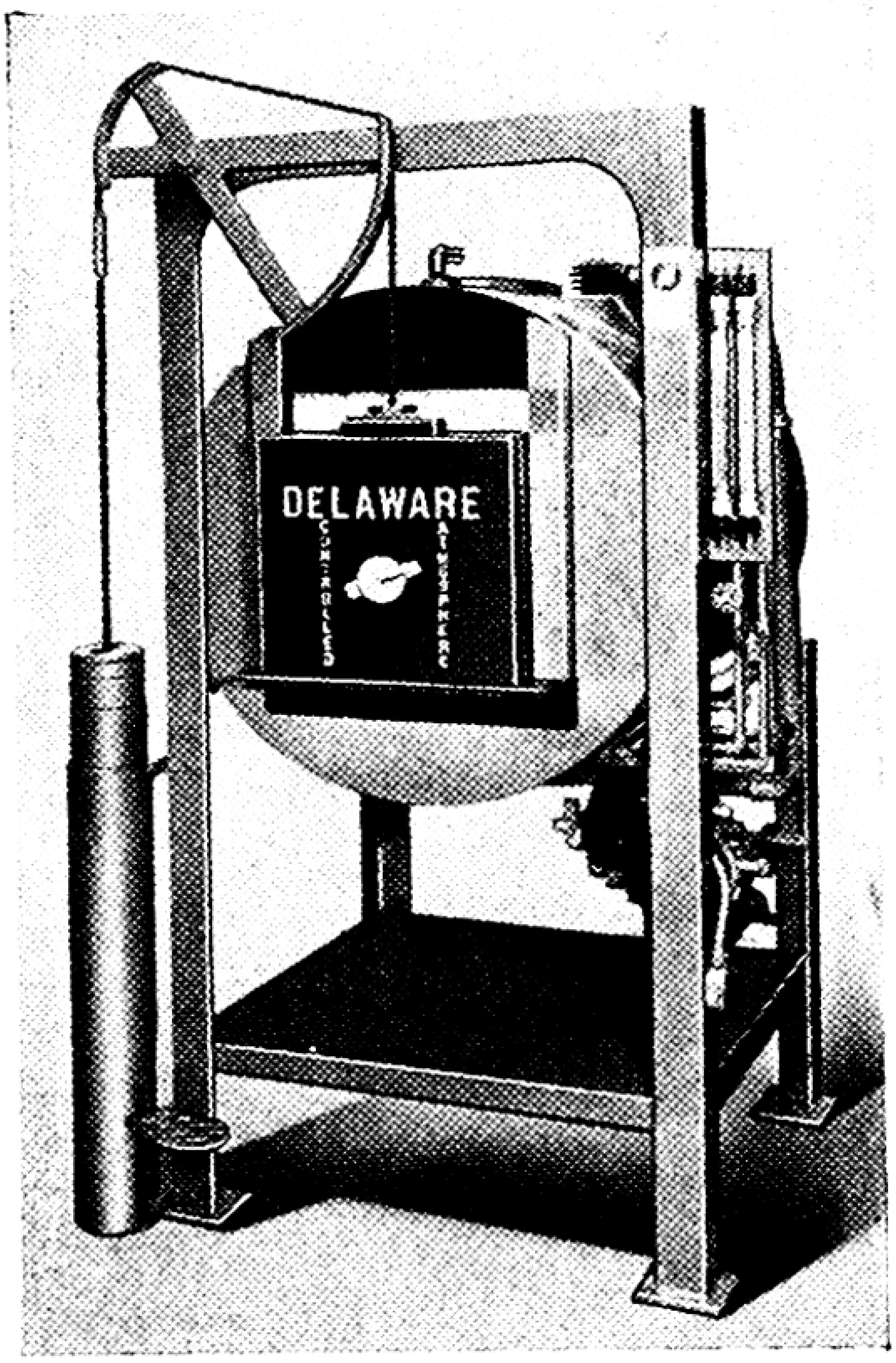


Fig. 13-4. Gas furnace with controlled atmosphere. *Courtesy Delaware Tool Steel Corporation.*

Liquid baths. The heat-treatment of metals by immersion in liquids capable of being maintained at treating temperatures is in common use. This method requires that the heating medium have no chemical effect on the immersed metal and that the medium itself does not change properties when kept at useful temperatures for prolonged periods.

Heat-treating in liquid baths has the advantages of a more uniform temperature, of faster heating, and of almost complete protection of the charge from the corroding effects of the atmosphere. The disadvantages may be listed as high cost, danger due to exploding steam, and the necessity of special mechanisms to hold metals immersed whose specific gravity is less than that of the liquid.

Heating mediums. The most-used heating mediums used in liquid baths are metals, salts, and oils. Lead is the only commercially used metal. The temperature ranges for these mediums are:

Salts: 350 F to 2350 F
Lead: 650 F to 1700 F
Oils: up to 500 F

Several points of comparison must be considered when the heating medium for a liquid bath is chosen.

The specific gravity of lead is about 10; that of the salts is near 2. Since most commercial metals are lighter than lead, they float, and therefore have to be held down. However, they sink in the liquid salt.

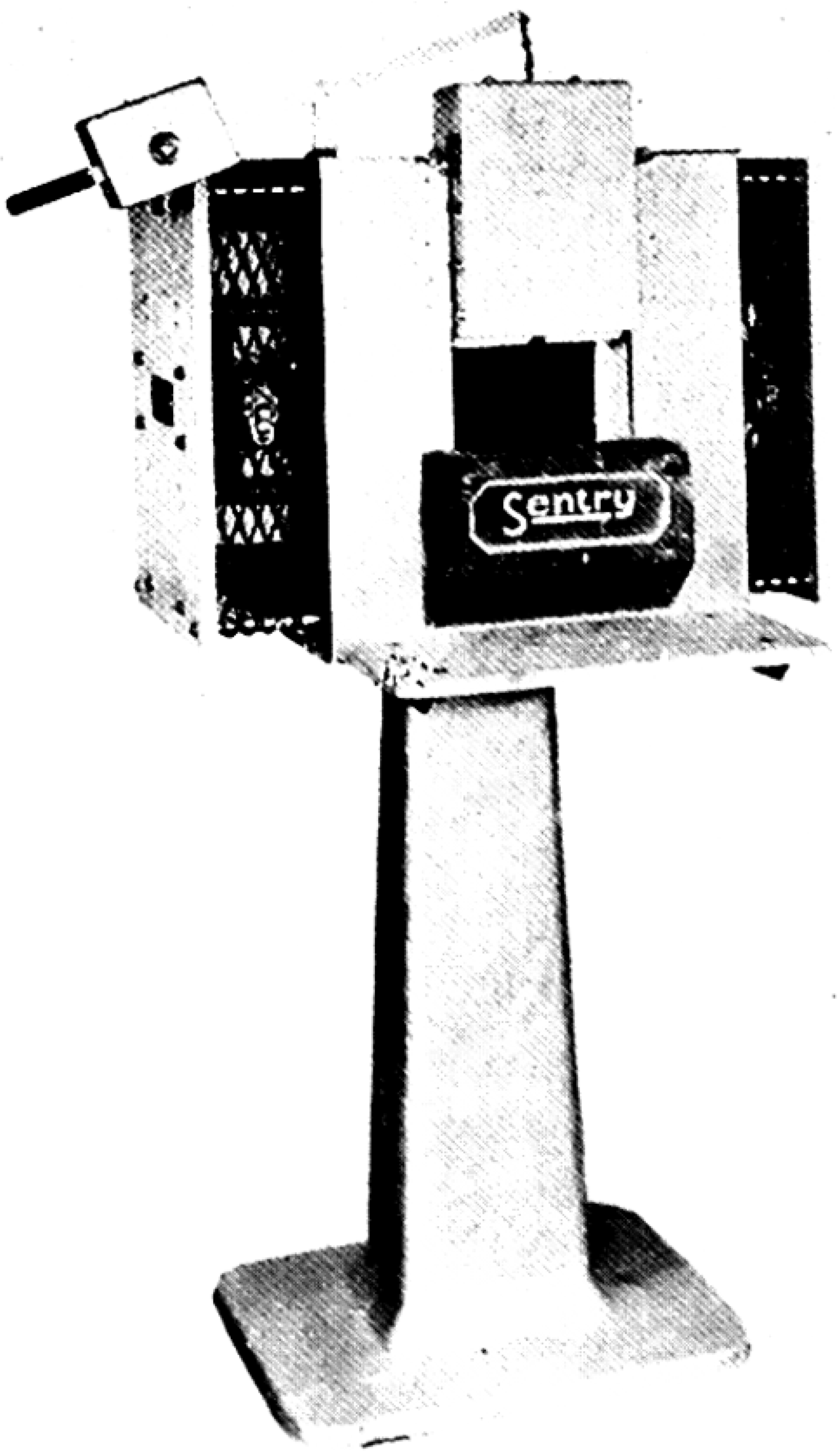


Fig. 13-5. Small electric furnace. *Courtesy The Sentry Company.*

The thermal conductivity of lead is higher than those of the salts. This advantageous property causes heat to be carried to the charge at a higher rate, making faster heating possible in lead.

Lead has a lower specific heat than the salts. Since the amount of heat stored up in a pound of lead at a given temperature is less than that for a pound of salts, there is apt to be a larger temperature change when charges are put in the furnace. This larger change is somewhat offset because the weight of lead in a given pot is much greater than the weight of the same volume of salts. If batch lots are being heated, this property of lead gives the advantages of faster heating and lower fuel consumption.

The formation of solid layers of the heating medium on the charge, because of its being cooled below the freezing point next to the cold charge, is affected by the melting point, the heat of fusion, and the thermal conductivity. Lead has a low melting point, which helps prevent solidification because of the greater change in temperature possible before solidification starts. Also, the high thermal conductivity of lead helps to keep the temperature near the charge high, since heat can be transmitted from remote parts of the bath at a faster rate. These advantageous properties are somewhat offset by the small heat of fusion of lead. Materials with small heats of fusion require the extraction of less heat in order to obtain complete solidification.

Although the temperature range of the salts is large, the range for any particular salt is narrow, making it necessary to change the heating medium for different kinds of charges. Since the temperature range of lead is large and covers most of the heat-treating temperatures, fewer changes of heating mediums are necessary.

Lead is chemically affected by the air much more than the salts, and generally needs the reducing protection of floating charcoal. On the other hand, lead has practically no corrosive effect on steel, whereas most salts do affect the steel surface. The effect on the pot is similar: lead has practically no effect, but most of the salts tend to destroy the lining.

Electric furnaces. These furnaces are heated by elements of the resistor type. Metal resistors are limited to about 1900 F because their life is rapidly shortened as the temperature rises above that point. Carbon resistors can be used where furnace temperatures up to 2300 F are necessary. The heating elements should be placed in the furnace so as to give uniform heating to the charge.

The advantages of the electric furnace over the fuel-fired furnace are:

1. No exhaust gases to dispose of; quieter and cleaner operation.
2. Easier temperature adjustment and better automatic and manual control.
3. More uniform temperatures under proper conditions.
4. Easier use of protective atmospheres.

The disadvantages are:

1. Slow temperature changes leading to difficulty in using where rapid changes are desirable.
2. High cost of electricity on a btu basis of comparison.
3. Long time necessary to heat to operating temperature.

Induction heating. In the past few years the application of induction furnaces to special and automatic work has increased tremendously. The method of induction heating transfers electrical energy to an isolated body, where it is changed into heat energy. This induced heat can be applied within definite areas with such speed and intensity that adjacent areas are unaffected.

Induction heating is particularly useful in treating small parts and confined areas of larger parts. It is also useful in the surface hardening of irregular surfaces, such as gear teeth, and can be used for brazing, annealing, and soldering work not possible by any other method.

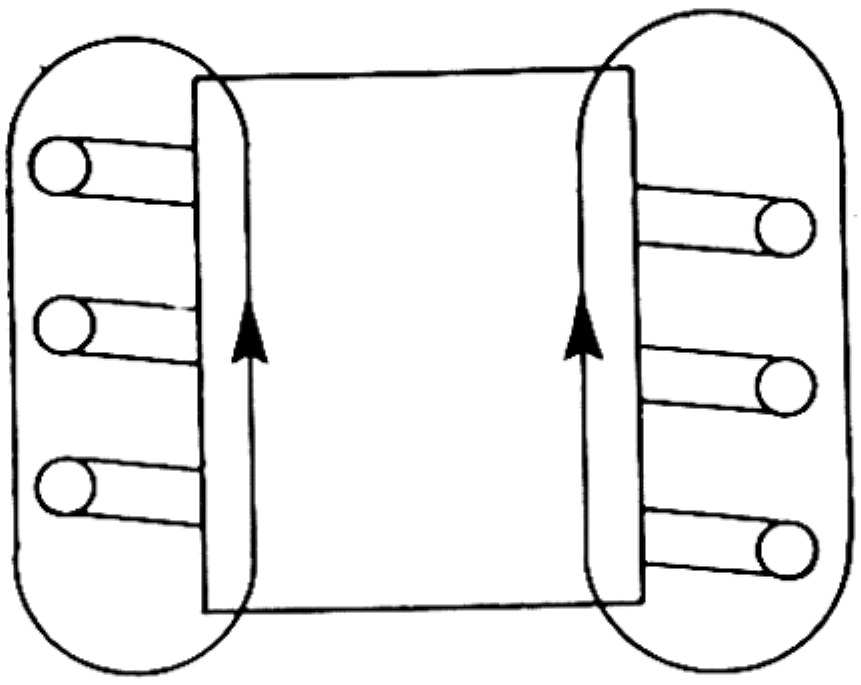


Fig. 13-6. Coil setup for induction-heating external surface of piece.

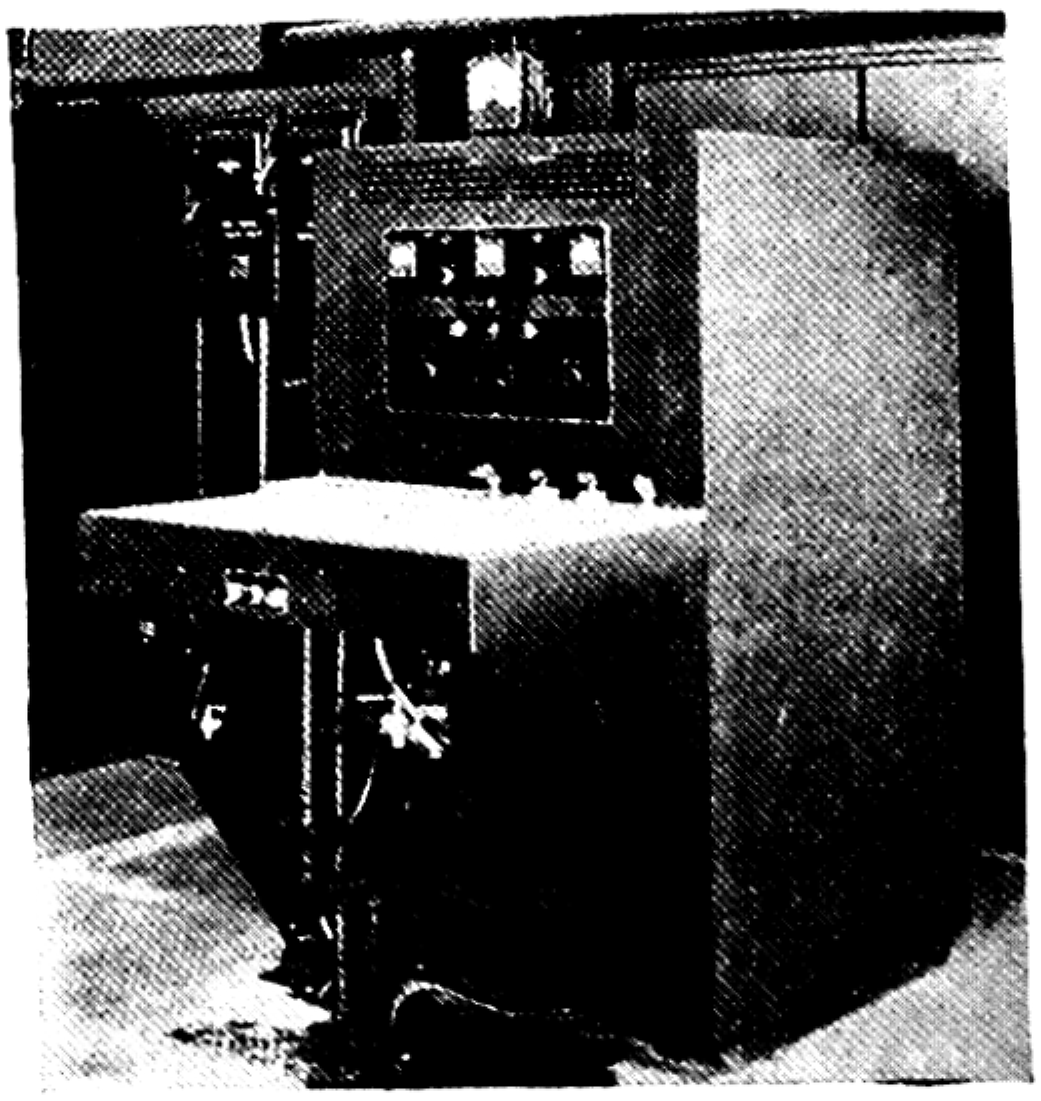


Fig. 13-7. A 15-kw output electronic induction heater with sink for quenching. *Courtesy General Electric Company.*

The source of high-frequency electrical energy can be supplied by a motor-generator set, spark oscillators, or electronic oscillators. Electronic oscillators can supply frequencies up to 300 megacycles. Figure 13-6 shows a setup for induction heating. High-frequency current passes through the coil, which induces current in the piece. This induced current is so large that it heats the piece. The depth of the heat depends upon the frequency and the heating time. The higher the frequency, the shallower the heat penetration; if the time is short, the heat will not be conducted away from the surface. Thus shallow penetration will again result.

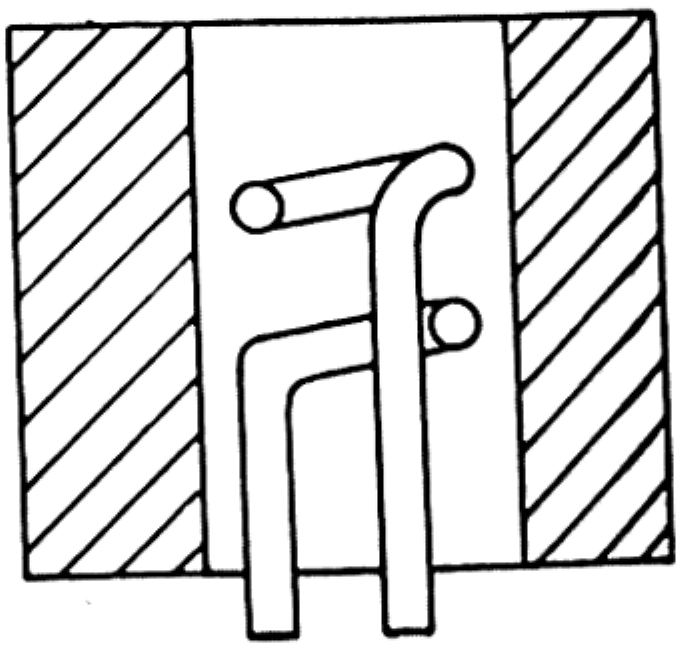


Fig. 13-8. Internal coil for hardening inside surface.

Induction heating can be applied to a great variety of special jobs. Figure 13-8 shows the heating of an inside surface without heating the outside. Figure 13-9 shows a gear setup for heating the surface of the gear teeth. Figure 13-10 shows the same gear being quenched. The metal parts of radio tubes and metallurgical samples placed in evacuated glass containers can be heated without atmospheric contamination.

Flame-hardening furnaces. Flame-hardening can be defined as the art of producing a thin, hard-wearing surface on an object by open flame-heating followed by immediate cooling. The process may be used on any part accessible to the flame. Cams, gears, and rails are good examples of products adaptable to flame-heating. The torch tips are usually combined with a suitable spray nozzle for cooling purposes.

The many special machines on the market fall into several general classes:

1. Stationary flame for hardening spots or for use where work is moved past the flame.

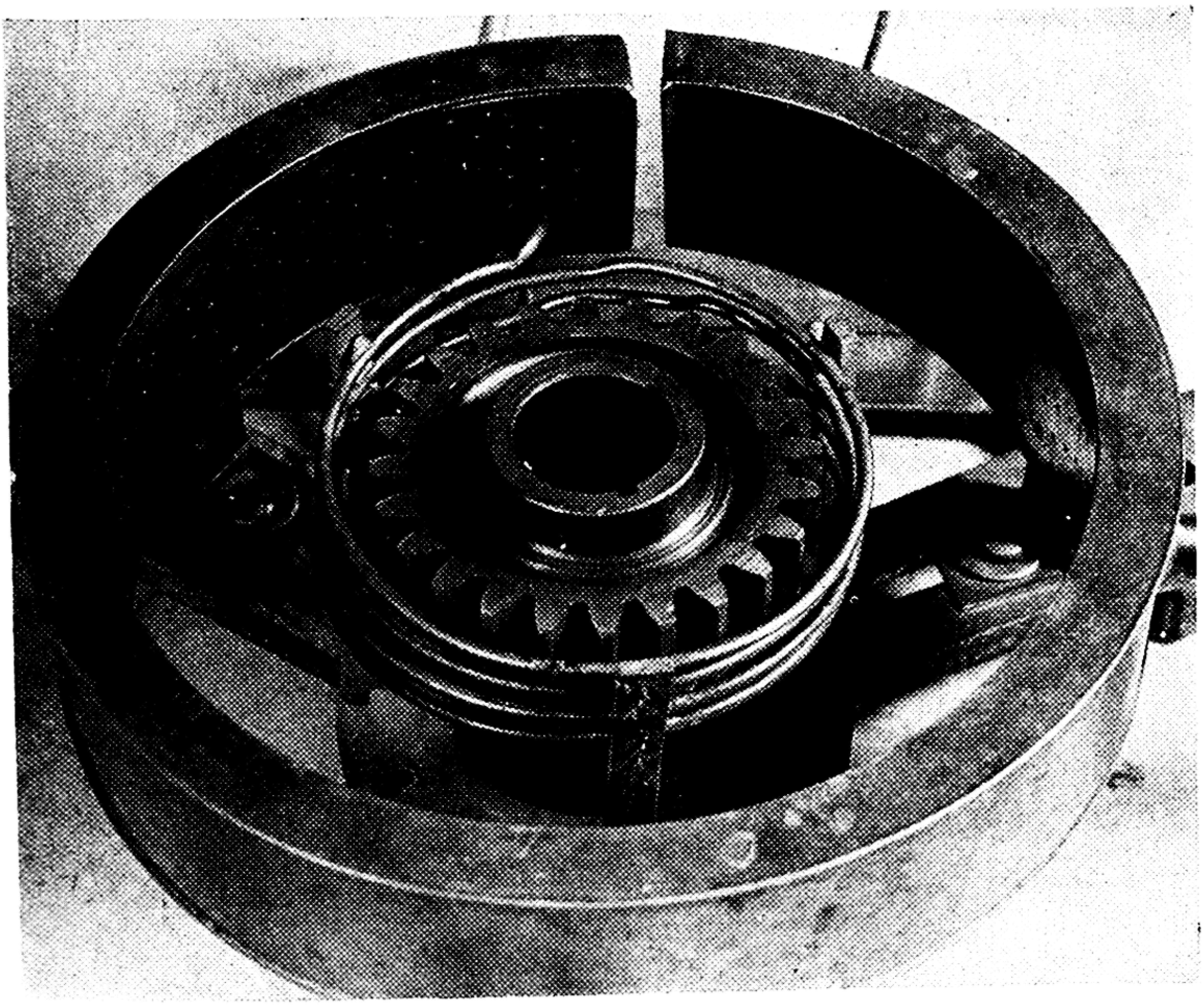


Fig. 13-9. Close-up of quench ring and heating coil with gear inserted in position. *Courtesy General Electric Company.*

2. Straight-line, moving flame and quench nozzle for hardening parts such as rails.

3. Circular-line, moving flame for hardening cams, gears, and so forth.

4. High-speed rotating part heated by several flame tips. When the part, such as a gear, is heated, it is dropped from the flame directly into the quenching liquid.

5. Stationary part and flame, with sufficient flame tips to heat the entire part at once, accompanied by a spray-quenching system.

The usual fuels are manufactured gas, natural gas, propane, and butane; air supplies the oxygen.

Atmosphere control. A very important phase of heat-treating where good surfaces are required is the control of the atmosphere in the furnace. Of the several methods of atmosphere control, the simplest is the control of the fuel-air mixture in open-flame and semi-muffle furnaces. A rich mixture makes CO and H_2 in the furnace; these gases are reducing agents. Damp H_2 also tends to decarburize steel, so a compromise must be made between decarburization and oxidation.

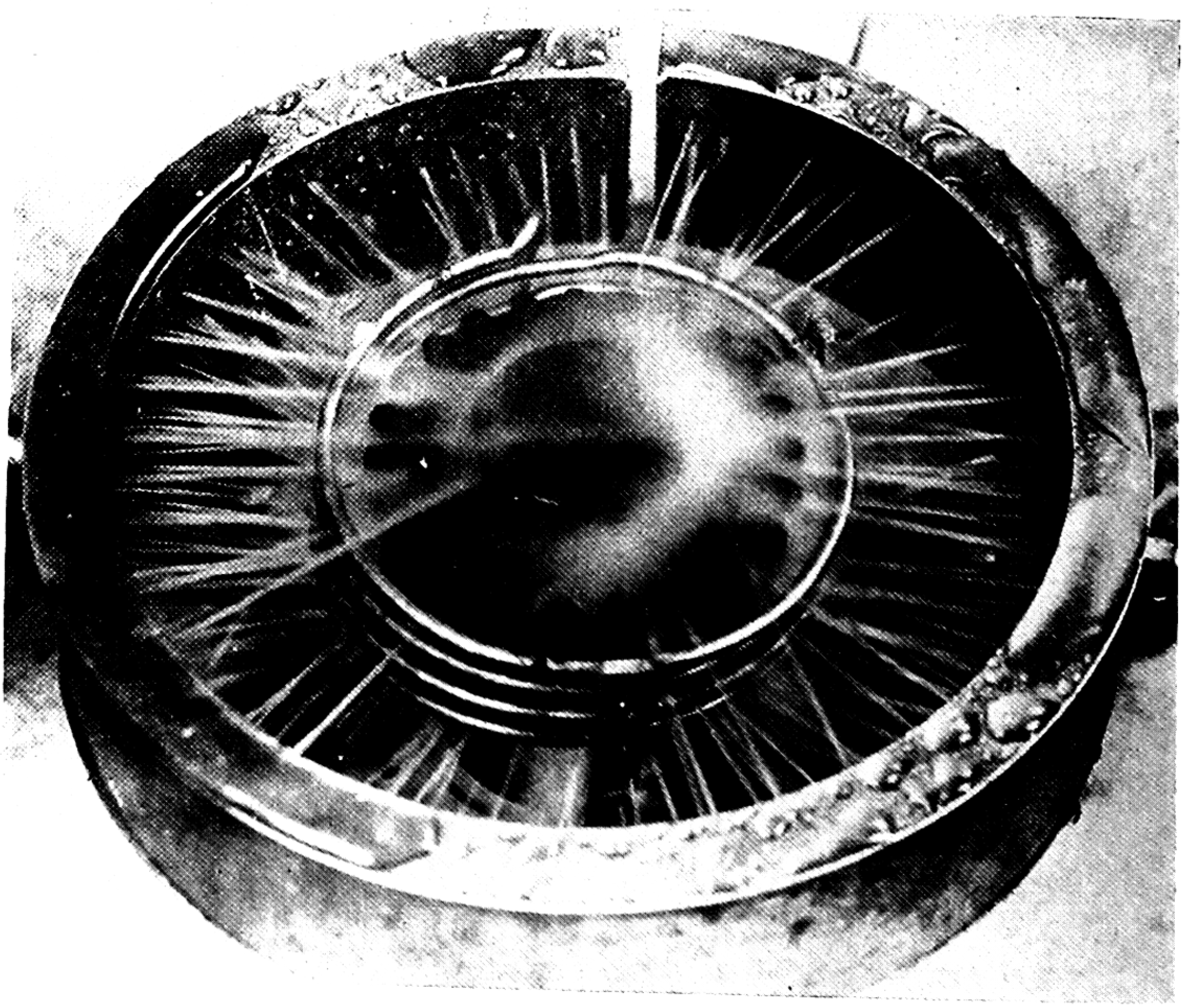


Fig. 13-10. Quenching operation is automatically controlled. *Courtesy General Electric Company.*

A better method is to fill electric or muffle furnaces with truly neutral gases. Among the common gases are H_2 made by electrolytic dissociation of water, dissociated ammonia, and gases made by partial combustion of hydrocarbon gases.

The use of lithium is fast coming into widespread use, particularly in the heat-treatment of steel and aluminum products. Small amounts of metallic lithium are placed in the furnace with the charge. As the fur-

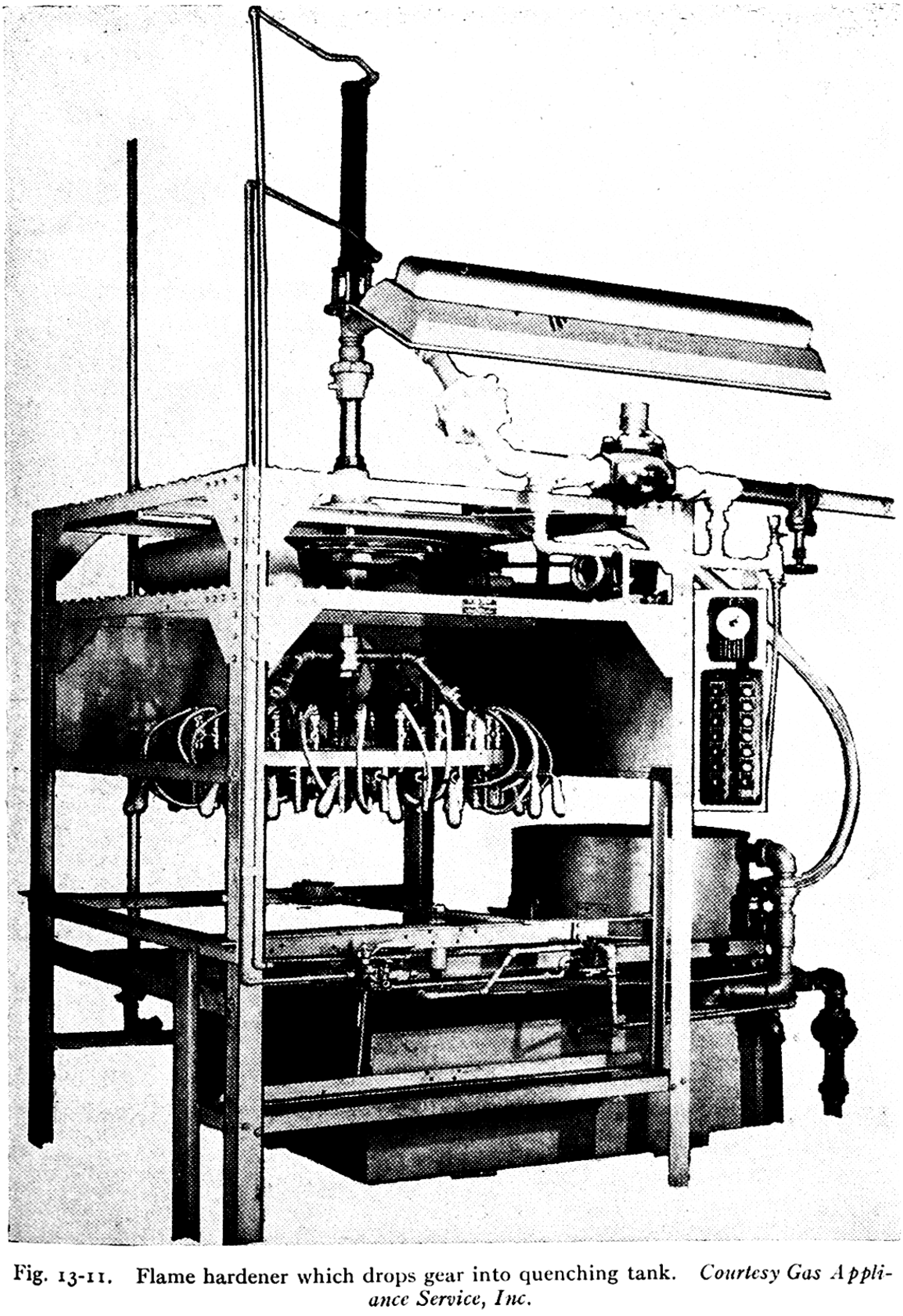


Fig. 13-11. Flame hardener which drops gear into quenching tank. *Courtesy Gas Appliance Service, Inc.*

nace heats up, the lithium vaporizes, forming a very active gas, and enters into the following reactions:

$$2Li + H_2O \rightarrow Li_2O + H_2$$
$$4Li + O_2 \rightarrow Li_2O$$

The lithium oxide is perfectly neutral, and the hydrogen is reducing. Thus a good furnace atmosphere is provided without expensive equipment.

A widely used method of atmosphere control for electric furnaces consists of placing the piece to be heated in a box made of a special carbonaceous material. These boxes, when heated to 2300 F, give off a gas at such a rate that neither carburization nor decarburization takes place. This method can be used with high-speed steels, particularly those containing cobalt and molybdenum. The major advantages of this method are its simplicity and low cost.

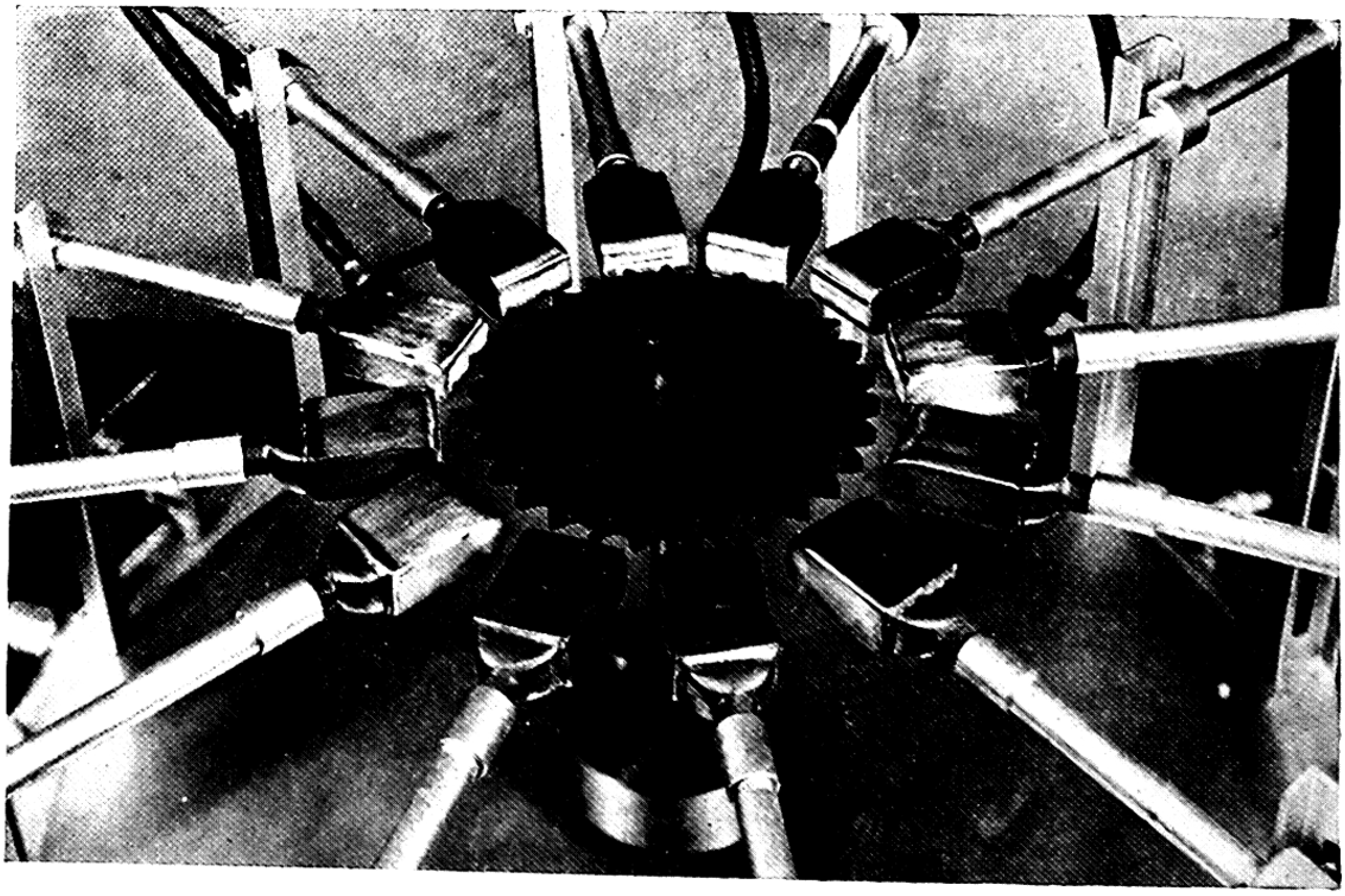


Fig. 13-12. Gas flame nozzles trained on a rotating gear to give uniform heating of all the gear teeth. *Courtesy Gas Appliance Service, Inc.*

Quenching fluids. The usual quenching fluids are salt solutions, water, oil, and air. These are listed in the order of decreasing cooling rate, although exceptions to the order arise when agitation of the medium and the temperatures of the metal and medium are fully considered.

The process of cooling in a liquid can be divided into three stages:

(1) *Vapor blanket cooling stage.* At this stage the metal is so hot that the quenching medium vaporizes at the surface of the metal, forming

a thin, stable, vapor film on the metal. Heat is transmitted through this film by conduction and radiation. Cooling is therefore relatively slow.

(2) *Vapor transport cooling stage.* This stage starts when the temperature of the metal is sufficiently cool that a continuous vapor film is not possible. The quenching medium wets the surface and commences to boil violently. The vapor bubbles thus formed are carried away from the metal surface by convection and gravity to be condensed by the surrounding cooler liquid. This is the most rapid cooling stage.

(3) *Liquid cooling stage.* This stage begins when the metal temperature is at the point where no vapor is formed, that is, near the boiling point of the liquid. Cooling is now carried on by convection and conduction. This is the slowest stage.

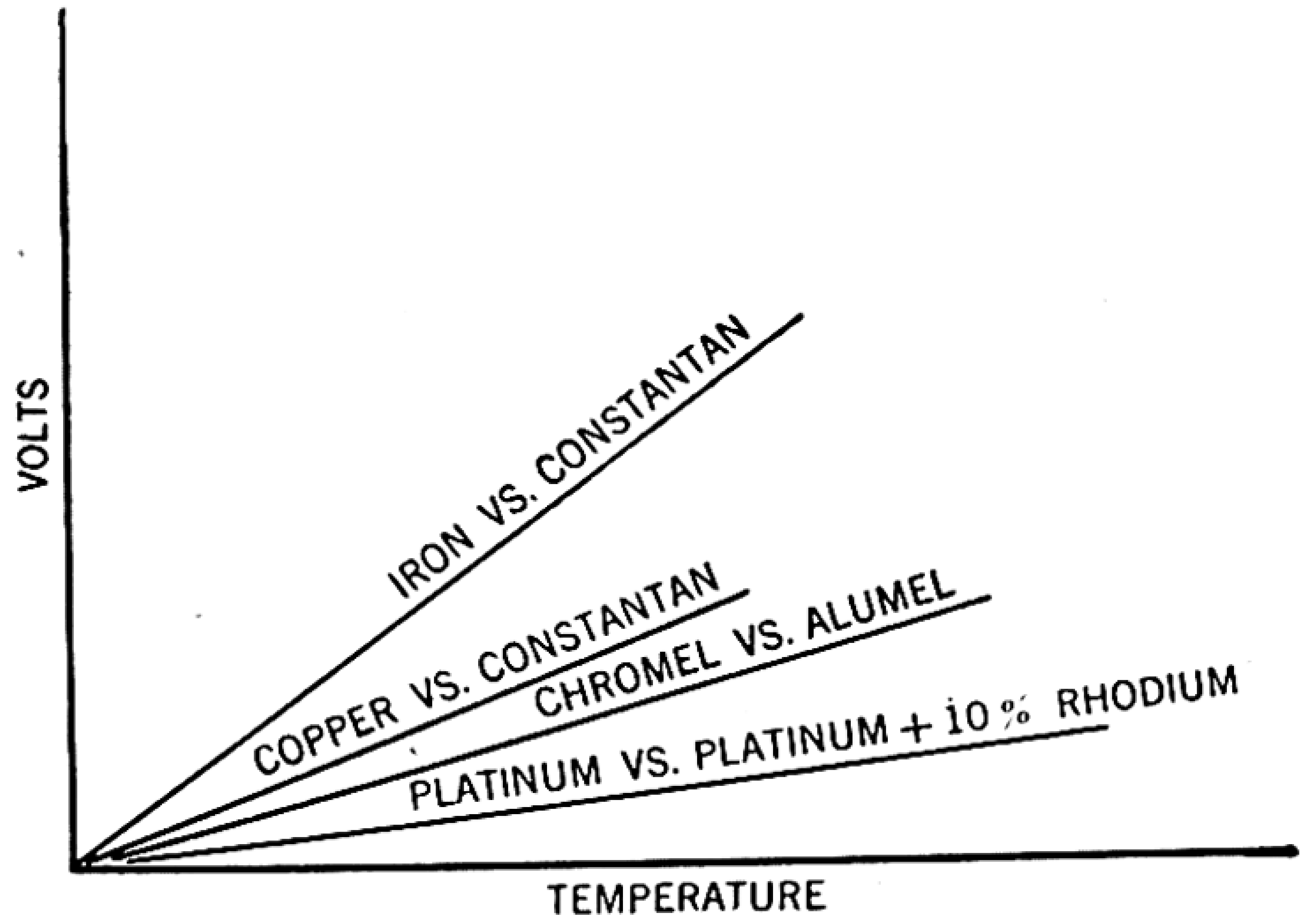


Fig. 13-13. The voltage-temperature characteristics of various thermocouple metals.

The ideal quenching medium should have a high initial cooling rate during the critical hardening range of the metal and a slow cooling rate below that range. Slow cooling in the last stage helps to prevent warping and cracking. The third major requirement of an ideal quenching medium is that it should not deteriorate with continued use.

Pyrometry. Pyrometry involves the measurement of temperatures above 950 F. The most-used methods employ thermoelectric, optical, and radiation pyrometer instruments.

In the thermoelectric pyrometer a thermocouple is placed in a position where its temperature accurately follows that of the furnace. A thermocouple consists of wires of two dissimilar metals which are joined together at both ends. Seebeck discovered in 1821 that if one junction (measuring junction) were heated while the other (reference junction) remained cool, a voltage was generated in the circuit which was proportional to the difference in temperatures between the two junctions. In use, the measuring junction is placed in the furnace; the reference junction may be just the connections to the voltage-measuring instrument leads or it may be placed in the ground to obtain a more constant temperature. The rate of change of voltage with temperature depends upon the choice of the two metals, as is indicated in Fig. 13-13. When the thermocouple is connected to a voltage-measuring instrument, the temperature may be read or recorded by using a conversion graph or by using a temperature scale on the instrument instead of a voltage scale.

The safe operating temperature for maximum service of a thermocouple depends largely upon the protection from the furnace atmospheres and upon the size of the wire. The length of life increases with the size of the wire. Platinum vs. platinum-rhodium thermocouples can be used up to 3000 F, but the iron vs. constantan and chromel vs. alumel combinations are best suited for the ordinary heat-treating temperature ranges from 1200 F to 2100 F.

Characteristics of thermocouples. Several characteristics limit the use the various types of thermocouples:

(1) The resistance to furnace gases at the temperature range for which the thermocouple was designed is an important consideration. The rate of oxidation increases very rapidly as the temperature rises. Therefore this factor limits the upper temperature of some metal combinations. Oxidation may be decreased by enclosing the wires in ceramic tubes which have a secondary protection of a metal tube. In general, iron-constantan thermocouples perform best in an oxidizing atmosphere. Conversely, some metals are so affected by a reducing atmosphere that the measuring characteristics change. Chromel-alumel thermocouples are best suited for reducing atmsopheres. Thermocouples must therefore be chosen to fit the furnace atmosphere of the particular furnace.

(2) When the temperatures are high for a particular thermocouple, recrystallization is apt to occur. Thus a change in the voltage-temperature characteristics takes place.

(3) A high melting point is desired in order to avoid the possibility of complete destruction of the thermocouple.

(4) Many metals are contaminated at high temperatures by the absorption of gases and other materials. This contamination changes the calibration of the thermocouples.

(5) A combination of metals giving the highest possible voltage is desirable. A high voltage makes the use of more rugged instruments possible and improves the sensitivity.

(6) The thermocouples should be easily made and reproducible in order to permit interchangeability.

(7) The thermocouples should follow the temperature changes as closely as possible in order that automatic temperature controls can hold the temperature within narrow limits. Large wire and protective tubes tend to delay the temperature change of the wire.

The choice of thermocouple materials is therefore based upon cost, constancy, and voltage characteristics.

Voltage measurements. The voltage measurements are usually made by either the direct-reading *millivoltmeter* or the more accurate *potentiometer*, which compares the thermocouple voltage with that of a standard cell. The millivoltmeter measures directly the voltage across the hot junction; the potentiometer requires an adjustment for each reading.

Recording devices. There is a variety of recording devices to choose from. They may in general be divided into two groups: (1) those using fluid ink in a pen which is constantly in contact with the chart, and (2) those which dot or print the chart by the periodic impression of an inked ribbon or carbon paper against the chart. This second group has three basic forms. The first is the *print hammer*, which may record the temperatures of several thermocouples on the same chart by means of a shifting multicolored ribbon. Each color represents one thermocouple. The second is the *print wheel*, which is a wheel having the type of several characters on the periphery. The wheel moves along the chart to indicate the temperature, and rotates to print the character which represents the thermocouple being recorded. The third is the *depressor-bar type*, which is particularly adaptable to the millivoltmeter or the galvanometer of a potentiometer. In this type, the millivoltmeter needle follows the temperature freely except when periodically pressed against the record by a depressor bar.

Optical pyrometers. An optical pyrometer is an instrument for comparing the brightness of a heated body with that of a standard source. The comparison is usually limited to a small part of the visible spectrum, usually red, since that is the brightest color at the low visible temperatures. The brightness of a heated body has a direct relationship to the temperature. Therefore, if that brightness is compared with the brightness of a calibrated standard, the temperature of the heated body may be determined.

There are two types of optical pyrometers: one uses a variable-intensity lamp as the standard source; the other uses a constant-intensity lamp as the standard source. Figure 13-14 shows the optics of a pyrometer with variable-intensity-lamp source. *S* is the hot body whose temperature is being measured. *L* is the objective lens which gathers and concentrates the light on the filament of the standard lamp *F*. *B* is a battery, and *C* is a variable resistance which controls the current in the filament and consequently its temperature. *E* is the eyepiece, and *R* is a filter which allows only red to pass through the telescope. The ammeter, *A*, has a scale which reads temperature. In operation, the telescope is focused on the source and the current is varied until the filament and the source are the same brightness. This point is reached when the filament seems to disappear in the image of the source. The temperature reading on the ammeter scale is the temperature of the source. This is so because the brightness of the filament depends upon the heat supplied by the electric current.

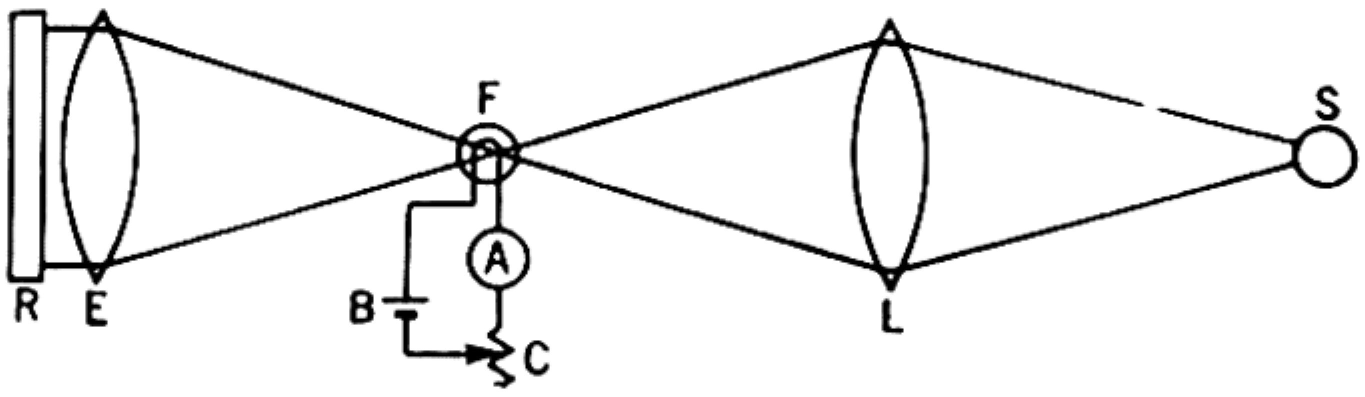


Fig. 13-14. Optical pyrometer with variable-intensity lamp.

The constant-intensity-lamp type is diagrammed in Fig. 13-15. The optics of this type are the same as for the variable-intensity type. The difference in this type is that the intensity of light from the source is varied until the filament seems to disappear. This intensity is varied by means of an absorbing wedge, the position of which indicates the temperature. The thicker the wedge in the light path, the less the intensity of light from the source.

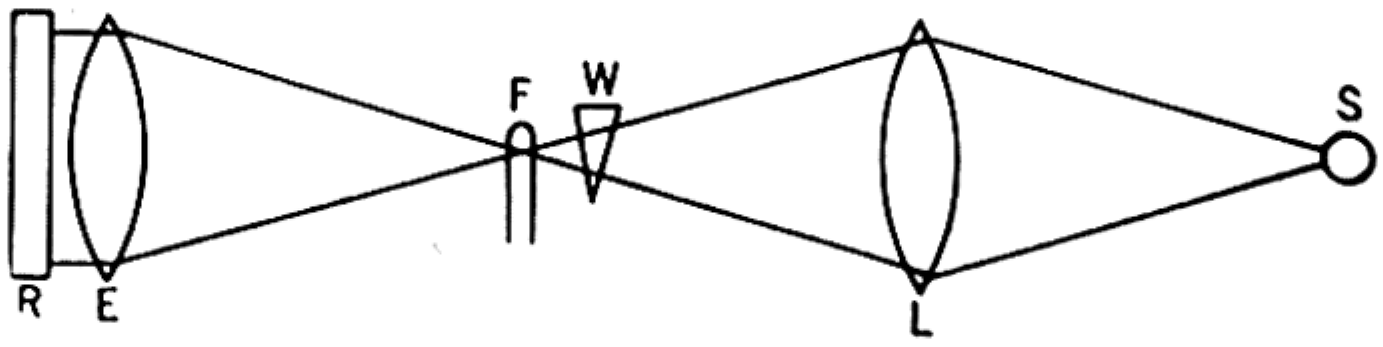


Fig. 13-15. Optical pyrometer with constant-intensity lamp.

Segar cones. Segar cones are cones made of materials of definite and varying melting points. Usually three of these cones are placed in a furnace. The melting points of these three cones vary slightly. When the lowest-melting-point cone melts, it indicates the approach of the correct temperature; when the next cone melts, the correct temperature has been reached. If the last cone melts, the temperature is too high.

A variation of this idea is a series of crayons the marks from which disappear at a given temperature. These are used in lower temperature ranges.

Summary and Definitions

The desired characteristics of a furnace are:

(1) Fast heating
(2) Close control of temperature
(3) Control of atmosphere
(4) Uniform heating
(5) High efficiency

The general types of furnaces are:

(1) Hearth
(2) Liquid bath
(3) Electric
(4) Flame-hardening
(5) Induction-hardening

Atmosphere control may be obtained by enriching the fuel-air ratio, by introducing such gases as N_2 and H_2 into the muffle, and by the use of metallic lithium in the muffle.

The choice of thermocouples depends upon their cost, their constancy, and their voltage characteristics. Voltage measurements may be made by millivoltmeters or by potentiometers.

The two general types of optical pyrometers are the variable intensity lamp comparison type and the constant intensity lamp comparison type.

Problems

1. What characteristics should a good heat-treating furnace have?

2. Discuss furnace fuels.

3. Compare the characteristics and uses of the open-flame, the semi-muffle, and the muffle furnaces.

4. Compare molten salts with lead for use in pot furnaces.

5. Name and discuss the advantages of an electrically heated furnace or a fuel-fired furnace.

6. Discuss the advantages and disadvantages of induction heating.

7. In what kind of work can flame-hardening be used to advantage?

8. What is the purpose of atmosphere control?

9. Discuss the use of lithium for atmosphere control.

10. Describe how a hot piece of metal cools in a quenching medium.

11. What are the desired characteristics of a thermocouple?

12. Discuss the various types of recording devices used in pyrometry.

13. What is the principle of an optical pyrometer?

Chapter 14

METAL TESTING

OVER A period of many years, standards have been devised and accepted which make it possible to have a universal understanding of specifications. The setting up of these standards involved the choice of the most appropriate tests, the design of testing instruments, and the design of the most significant and reliable test specimens. X-ray diffraction and spectrographic methods have been improved sufficiently to be used as routine checks on the grain structure and composition of metals; radiography and magnetic methods are used for the detection of defects. Many other methods have been developed for production checks on the composition and grain structure of metals. These are based on the effects on the magnetic properties of a metal caused by the passage of an audio-frequency alternating current through a surrounding coil. Very brief descriptions of some of these tests and inspection methods will be discussed in this chapter. Chapter 2 should be reviewed at this point.

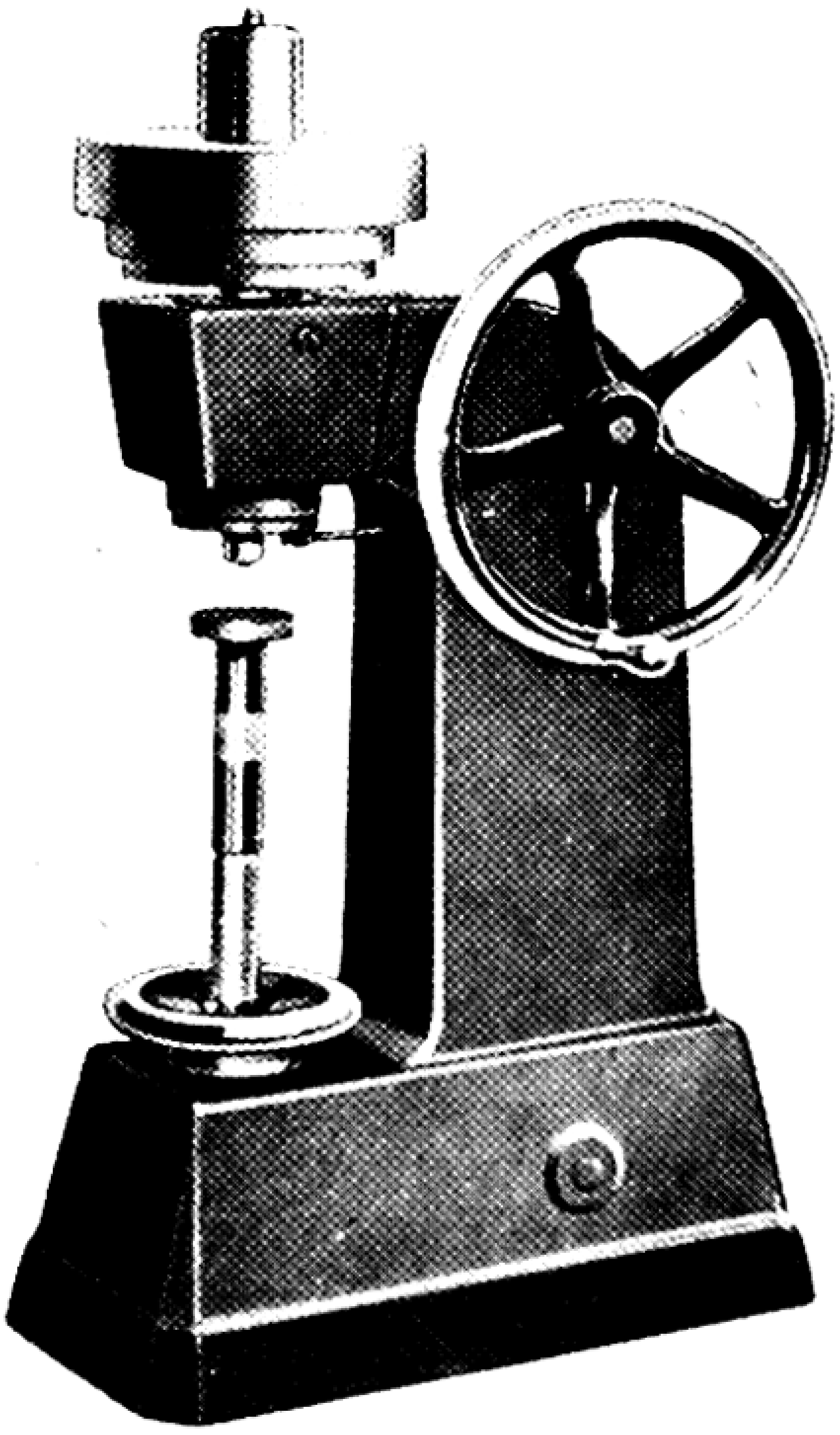


Fig. 14-1. Hydraulic Brinell hardness tester. *Courtesy Riehle Testing Machines Division, American Machine and Metals, Inc.*

Hardness. The most popular tests for hardness are based upon the ability of a metal to resist indentation, although some other tests in common use are based upon resilience.

The *Brinell hardness tester* consists essentially of an anvil for holding the specimen to be tested and a loading device which forces into the surface a hardened steel ball 10 mm. in diameter. The area of the impression is the measure of the hardness of the specimen. The loading device is usually a hydraulic press; the load on the ball is indicated by a Bourdon gage or by the lifting of a dead weight, as is shown in Fig. 14-1. Loads of 3000 kilograms for hard metals and 500 kilograms for soft metals are generally used, but since the hardness number is defined as the ratio of the load in kilograms to the area of the impression in square millimeters, it is not absolutely necessary to use these loads.

The operating method is first to clean the surface to be tested, for if scale or sand is on the surface it may affect the reading. Next, the correct load is applied; 30 seconds with the 3000-kilogram load, and 60 seconds with the 500-kilogram load. If a high accuracy is desired, the dead weight should be spun around to eliminate friction. Finally, the diameter of the impression is measured with a special microscope (Fig. 14-2) and used in the following formula for the Brinell hardness number. The diameter to be used in the formula is the average of two readings taken at right angles to each other.

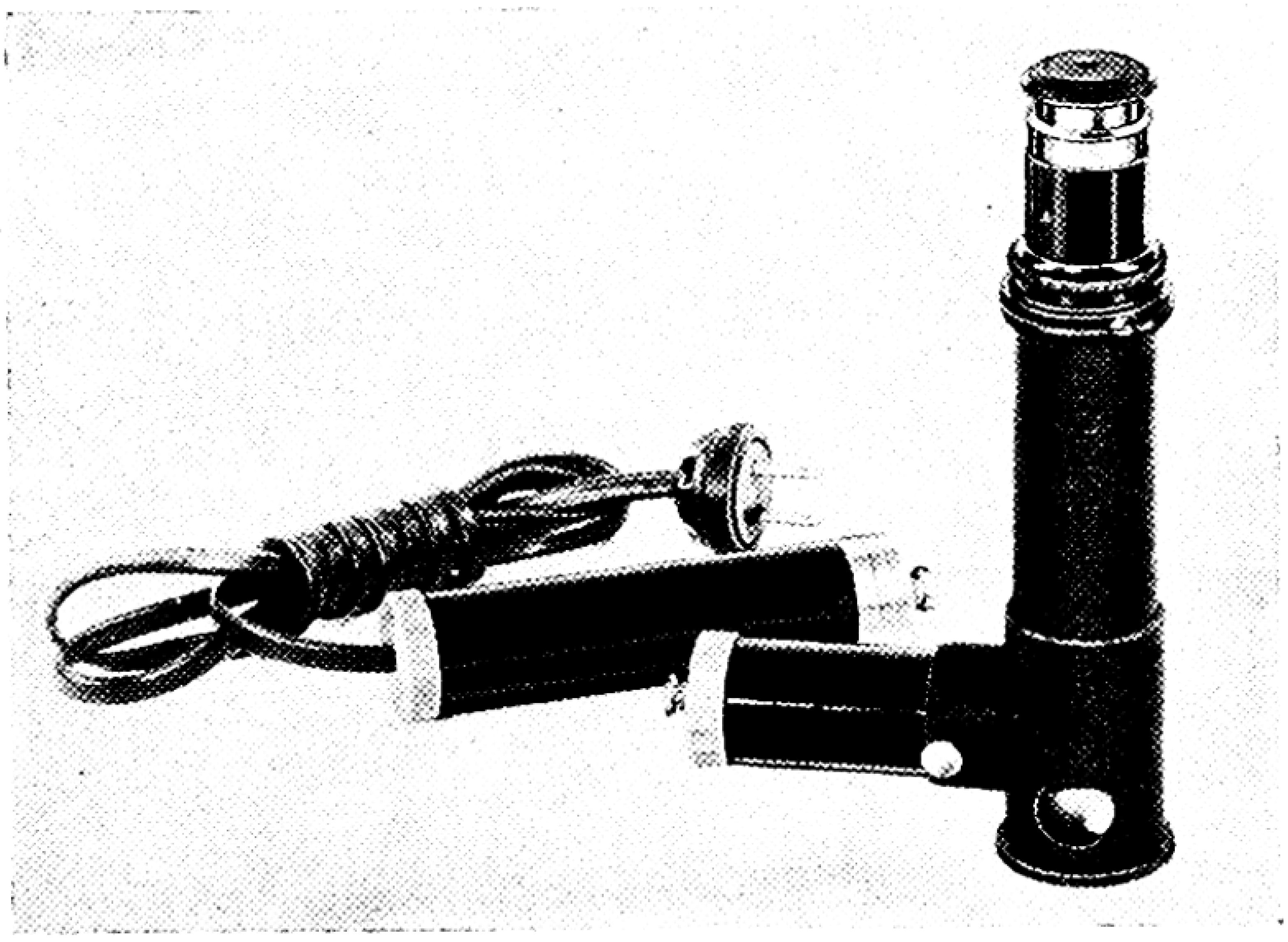


Fig. 14-2. Brinell microscope. *Courtesy Bausch & Lomb Optical Co.*

$$H = \frac{P}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

where H = Brinell hardness number
P = Load in kilograms
D = Diameter of ball in millimeters
d = Diameter of impression in millimeters

If test results are to be consistent, certain precautions are necessary.

The test should not be used on steel samples less than one-half inch thick or so near to the edge that the edge bulges out.

Many tables have been published which give the relationship between the impression diameter and the hardness number, and also between the Brinell hardness number and other hardness numbers.

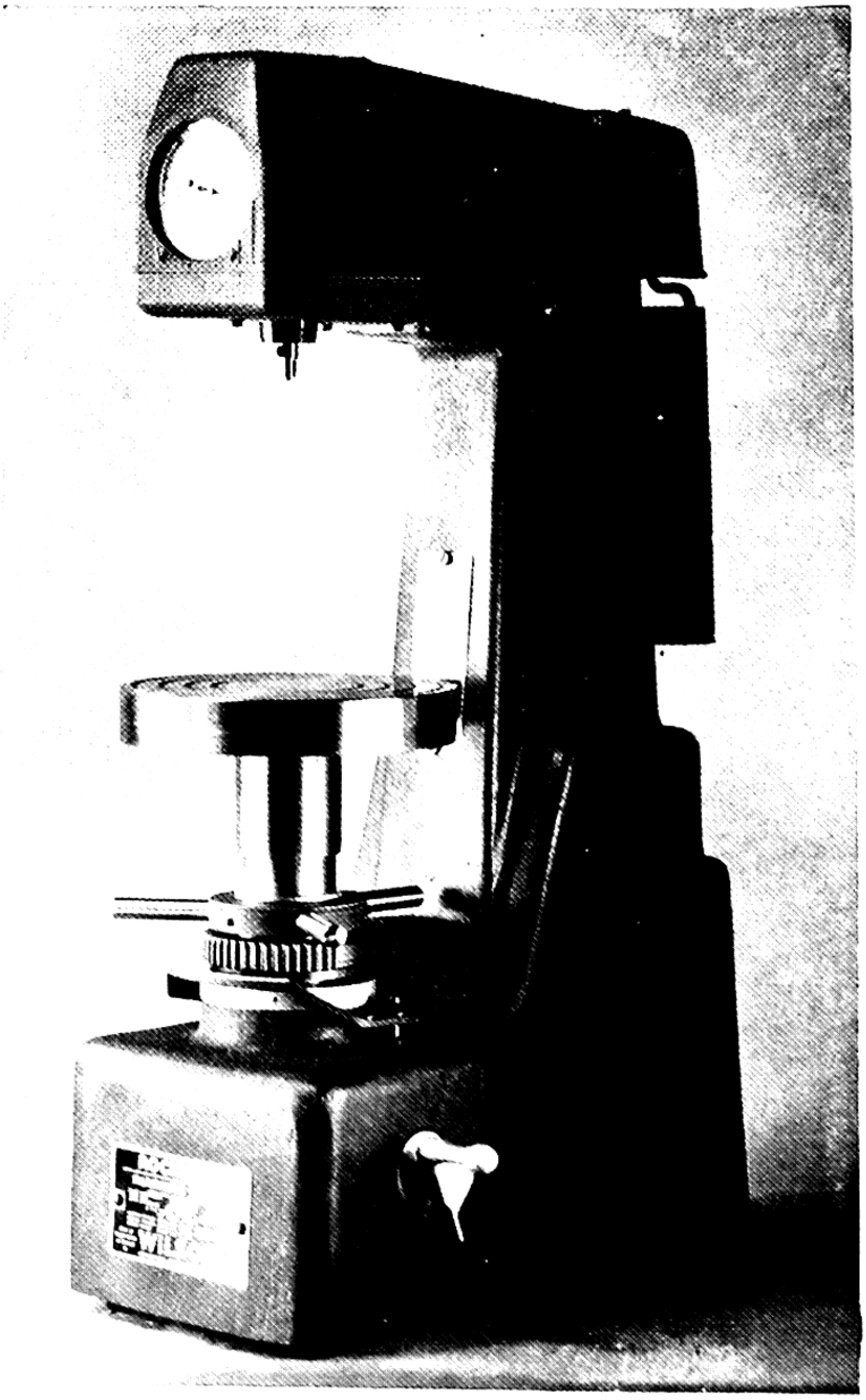


Fig. 14-3. Rockwell hardness tester. *Courtesy Wilson Mechanical Instrument Co., Inc.*

The *Rockwell hardness tester* (Fig. 14-3) measures the residual depth of an impression which is made by a steel ball or a diamond cone under specified load conditions. The numbers are based upon the difference in the depth of impression of a specified major load and a 10-kilogram minor load. The operation of the tester is first to apply a 10-kilogram load, which seats the penetrator and tends to eliminate surface differences, and then to set the depth gage dial at the point marked "Set." Next, the major load is applied and then removed. The major load is removed in order to eliminate the effect of the deflection of the tester frame. The dial reads the Rockwell hardness number directly.

Before a specimen is tested, scale and rough surfaces should be removed by grinding or machining. There is a minimum thickness which can be tested with accuracy. The effect of the penetrator should not be noticeable on the back side of the test piece. When tests are made on curved surfaces, the radius of the surface should also be given.

Several scales of Rockwell hardness numbers depend upon the size of the penetrator and the load. The choice of the scale depends upon the hardness and condition of the metal to be tested, but the *B* and *C* scales are generally regarded as standard. The *B* scale uses a 60-kilogram load and $\frac{1}{16}$-inch diameter ball penetrator; the *C* scale uses a 150-kilogram load and the diamond cone brale.

When materials are too thin to measure with the standard Rockwell tester, a special tester can be used with loads as light as 15 kilograms. This is known as the *Rockwell superficial-hardness tester.*

The *Scleroscope hardness number* is based upon the rebound height of a diamond-tipped hammer which has fallen through a given distance upon the surface to be tested. In order to insure consistent readings, the surface should be smooth and level, and the instrument should be held steady.

As a rough check on hardness, a file can be used. If a file has a hardness of about 65 C on the Rockwell *C* scale, any material the file does not scratch must be harder; any material it does scratch is softer. An experienced operator can estimate the hardness rather closely by the ease with which a file scratches the test piece.

The *Vickers Pyramid hardness testing machine* is similar in theory to the Brinell tester in that the hardness number is based upon the ratio of the load to the area of the impression. The penetrator, instead of being a steel ball, is a diamond pyramid having an angle of 136° between the faces. The loads can be varied from 1 to 120 kilograms, according to the thickness and hardness of the material to be tested. This type of tester has the following advantages:

(1) The impressions are geometrically similar for all depths of penetration.

(2) The deformation of the diamond is practically zero.

A very small *Vickers type brale* is sometimes used for micro-hardness testing. Such a tester can measure the hardness of individual grains, thus making possible a differentiation between the hardness of different grains rather than taking an average value for several grains.

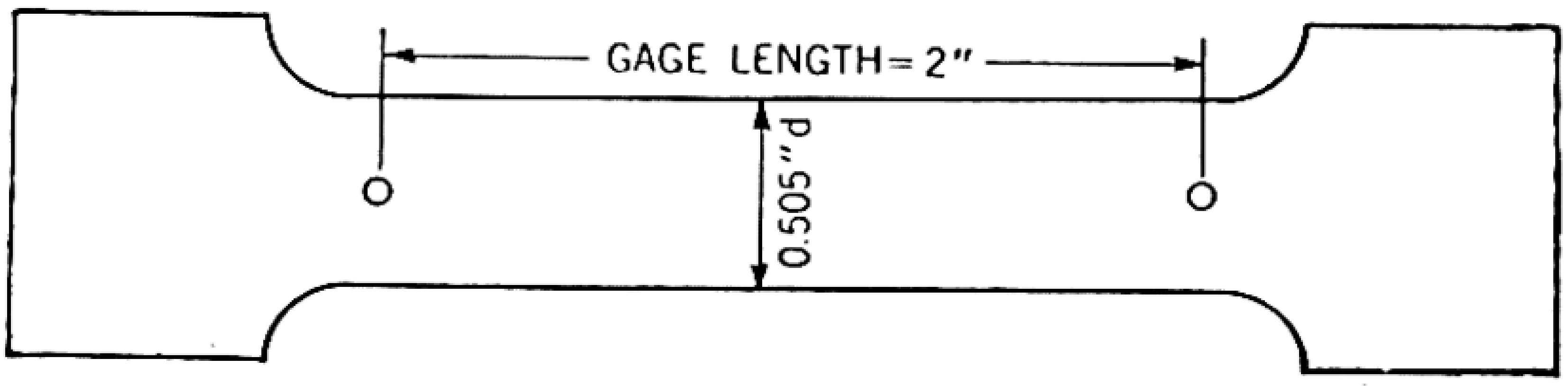


Fig. 14-4. Tensile specimen.

Tensile tests. The tensile test is perhaps the most useful of all the tests from a design point of view. Pulling one standard specimen in such a manner as to give a good stress-strain diagram will give the following information: modulus of elasticity, approximate elastic limit, yield point, ultimate tensile stress, breaking stress, reduction of area, percentage elongation. Other information can be obtained from the type of fracture.

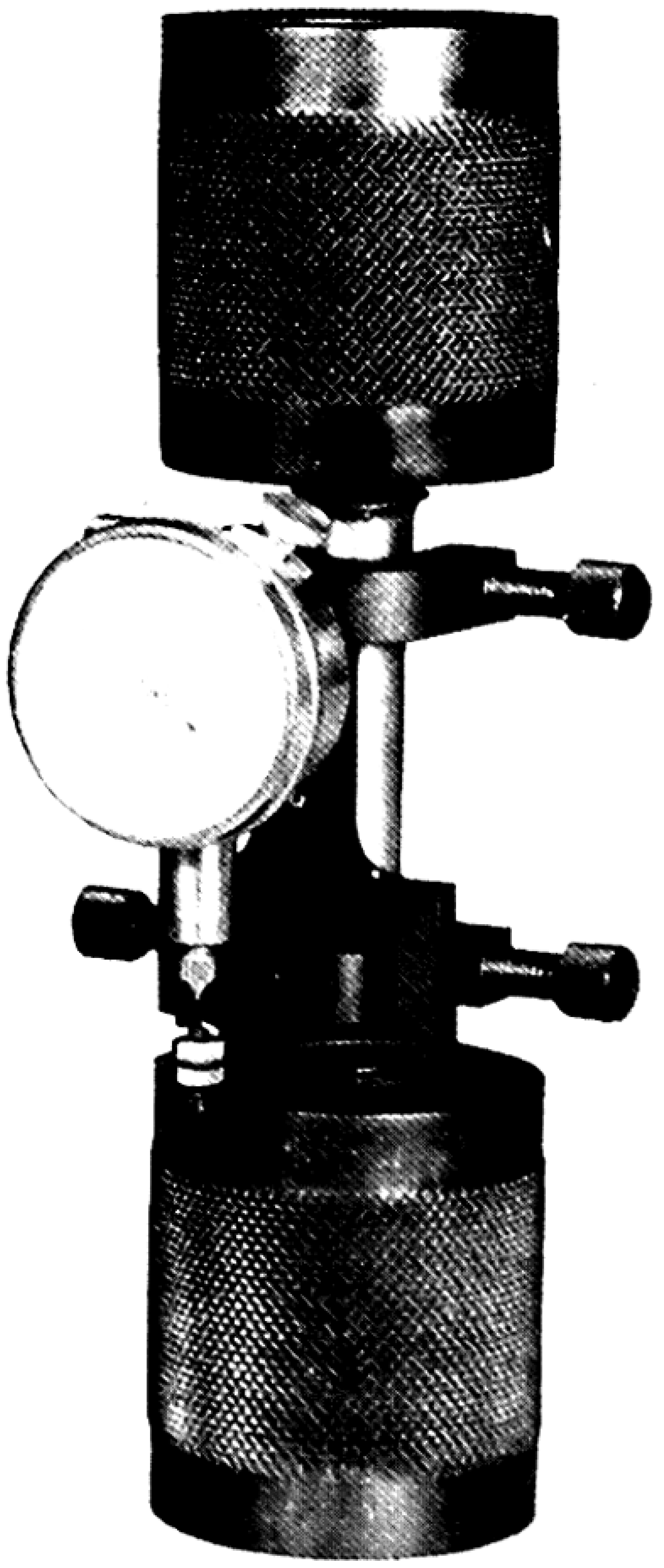


Fig. 14-5a. Two-inch dial averaging extensometer. *Courtesy Riehle Testing Machines Division, American Machine and Metals, Inc.*

Usually the test specimen is made to a standard specification, such as that shown in Fig. 14-4. Sometimes specimens of casting metals are made in a mold and tested without machining. The usual gage length for obtaining the percentage elongation is two inches. Punch marks two inches apart are made on the specimen before it is pulled. To find the permanent elongation, the distance between the marks is measured after the specimen is fractured.

In order to plot a stress-strain diagram, the strain for each stress reading must be recorded. Both mechanical and electronic recorders are available which automatically plot the curve. Another method is to use an extensometer (Fig. 14-5) to obtain the strain as the corresponding loads are read from the load dial. Ordinarily, the unit stresses are used

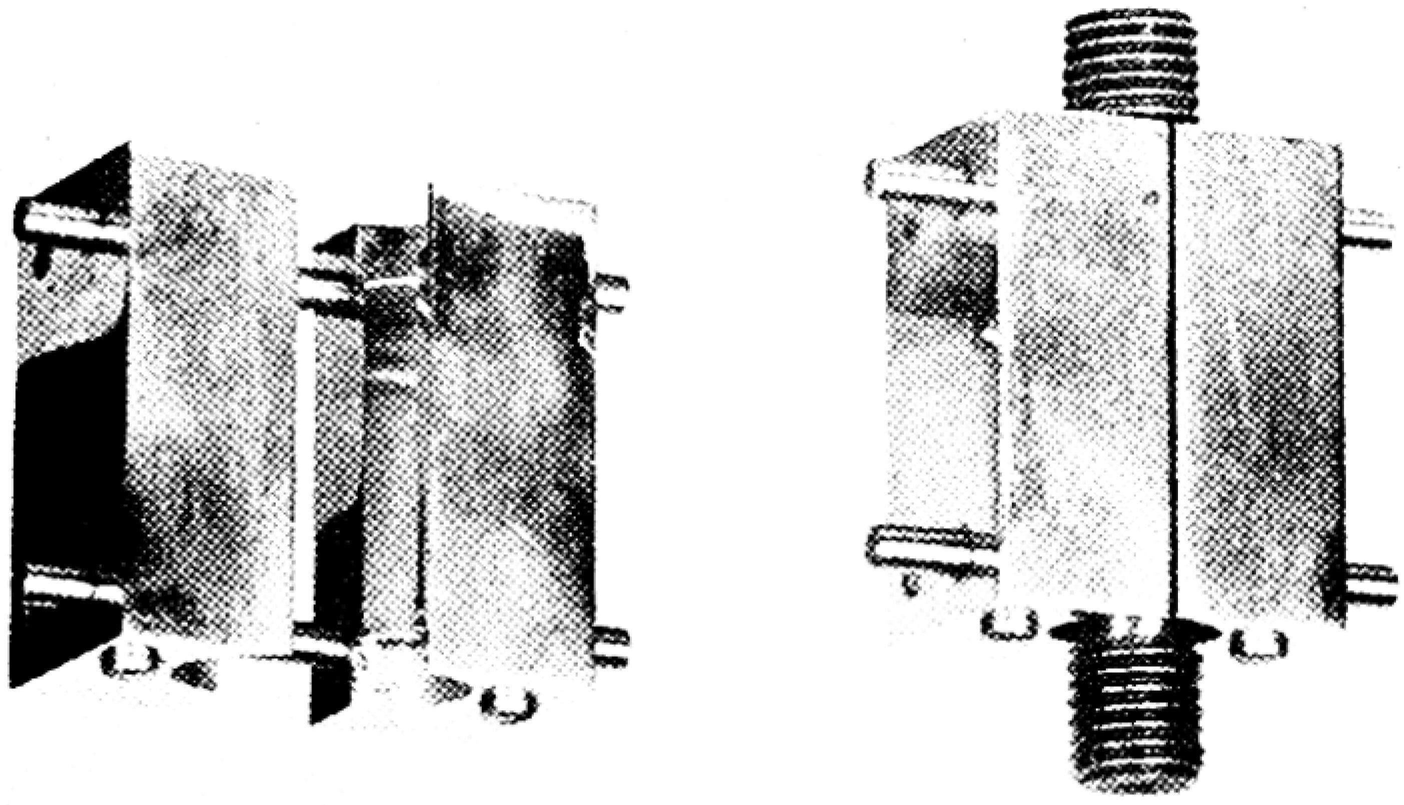


Fig. 14-5b. Two-inch marking block (open and closed views). *Courtesy Riehle Testing Machines Division, American Machine and Metals, Inc.*

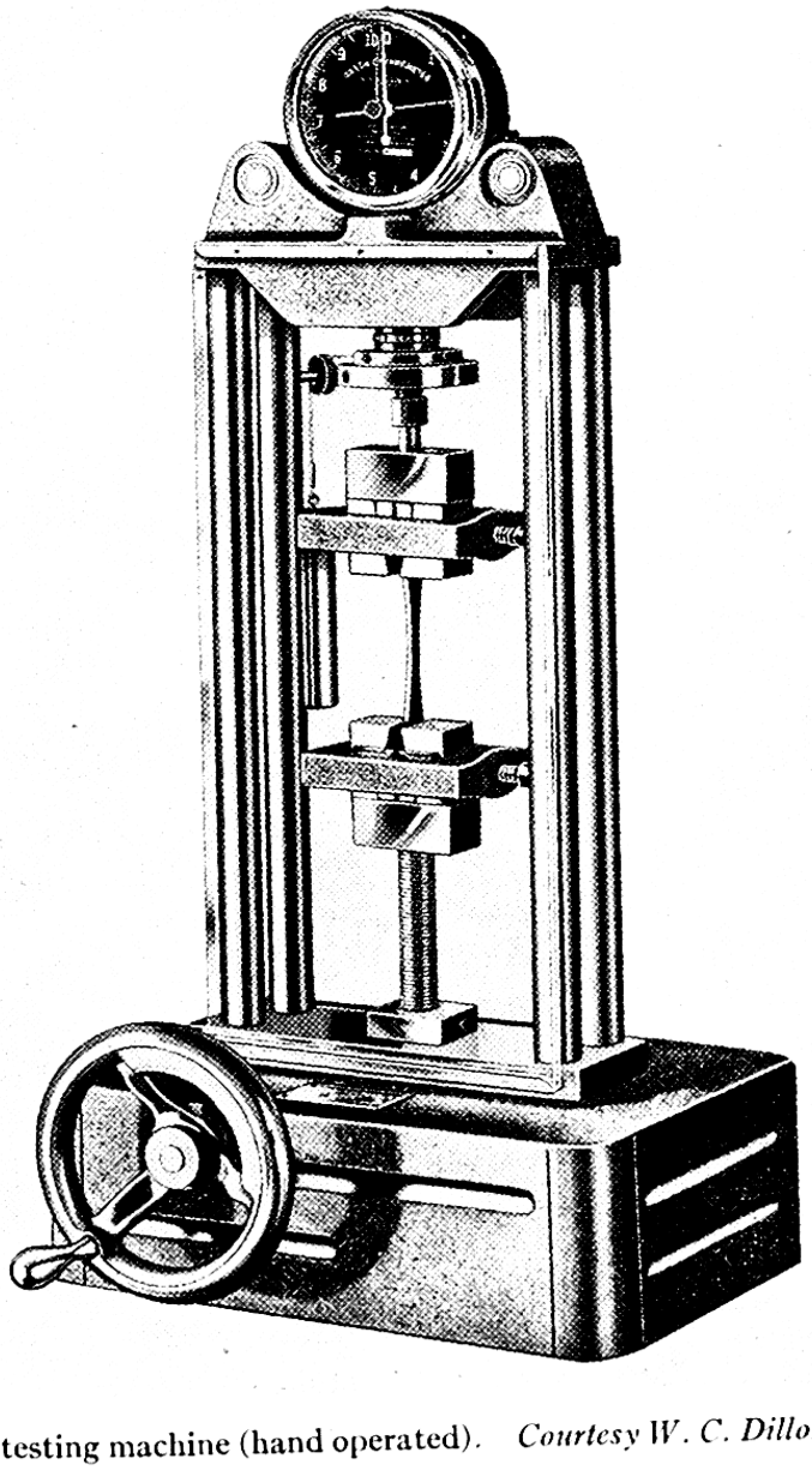
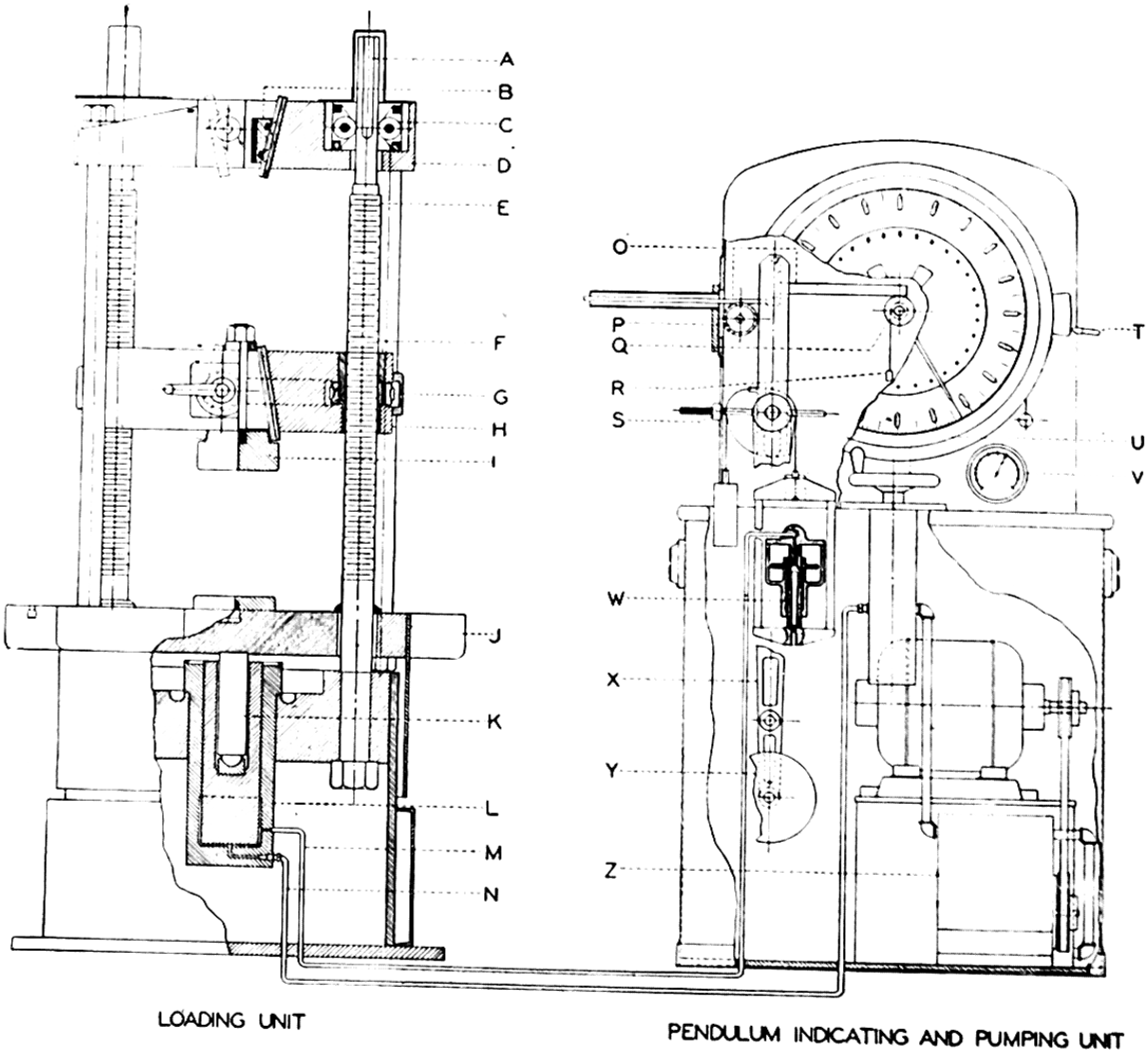


Fig. 14-6. Small testing machine (hand operated). *Courtesy W. C. Dillon & Company, Inc.*

for the ordinates of the curve; unit strains are used for the abscissas. This system makes possible the easy comparison of curves from different sources and from different sized specimens.



A—Upper roller bearing guide.
B—Wedge grips.
C—Upper guide rollers.
D—Upper pulling head.
E—Non-rotating screw columns.
F—Bronze nuts rotated by individual motor drive for adjusting purposes of lower pulling head.
G—Worm gear.
H—Lower pulling head.
I—Solid compression tool.
J—Compression and transverse table.
K—Spherical connection to center of plunger.
L—Floating packless ram.
M—Oil line leading to measuring cylinder.

N—Supply line leading to orifice control.
O—Indicator rack.
P—Indicator rack supporting roller.
Q—Pointer pinion.
R—Counterweight to eliminate backlash.
S—Zero adjustment.
T—Scale range selector.
U—Handwheel for stepless regulation of testing speeds.
V—Dial indicating rate of load per minute of pacing disc.
W—Floating type measuring cylinder unit transmitting load to pendulum.
X—Pendulum arm.
Y—Removable pendulum weight.
Z—Pumping or power unit.

Fig. 14-7. Diagram of hydraulic testing machine. *Courtesy Riehle Testing Machines Division, American Machine and Metals, Inc.*

The stress-strain curve gives information concerning the modulus of elasticity, the yield point, the ultimate stress and other points, but sometimes it is not convenient to take the necessary data. Since some specifications ask only for the yield stress and the ultimate stress, a

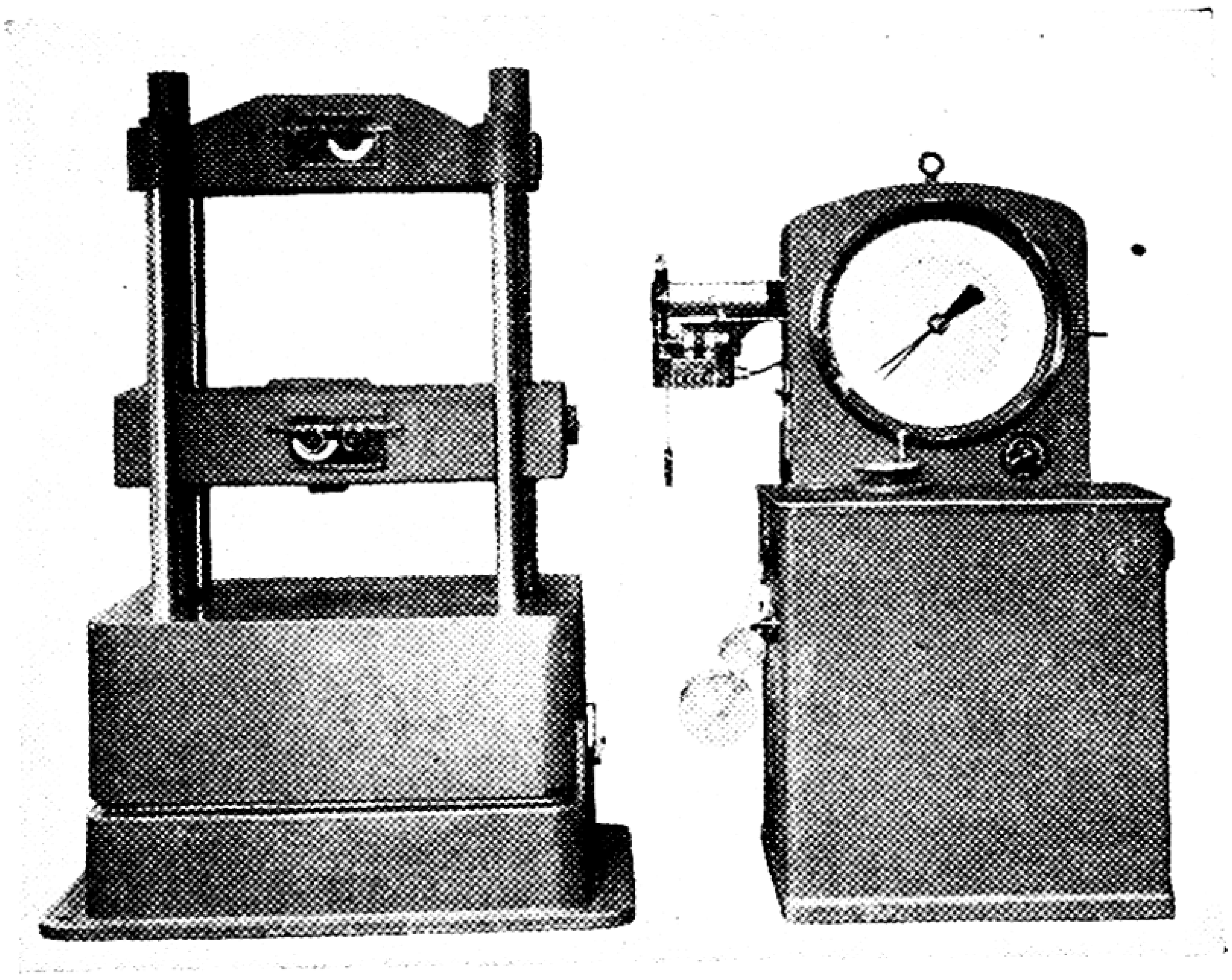


Fig. 14-8. Hydraulic testing machine. *Courtesy Riehle Testing Machines Division, American Machine and Metals, Inc.*

simpler method can be used. The ultimate stress can be read directly on the load dial, and the yield stress can be found by use of a pair of dividers. A prick-punch mark is made near one end of the specimen and the dividers are set at two inches. One point of the dividers is set in the punch mark and the other end is used to scratch a mark on the specimen. The load is then slowly applied, and the free point of the divider continuously scratches the specimen. The moment it is noticed that the scratch is widening, the yield point has been reached. Actually, a strain exists before the yield stress, but it is so small that it is not noticeable. The reduced diameter for figuring the percentage reduction in area is found by placing the fractured parts together and measuring the minimum diameter of the necked-down section with thread micrometers.

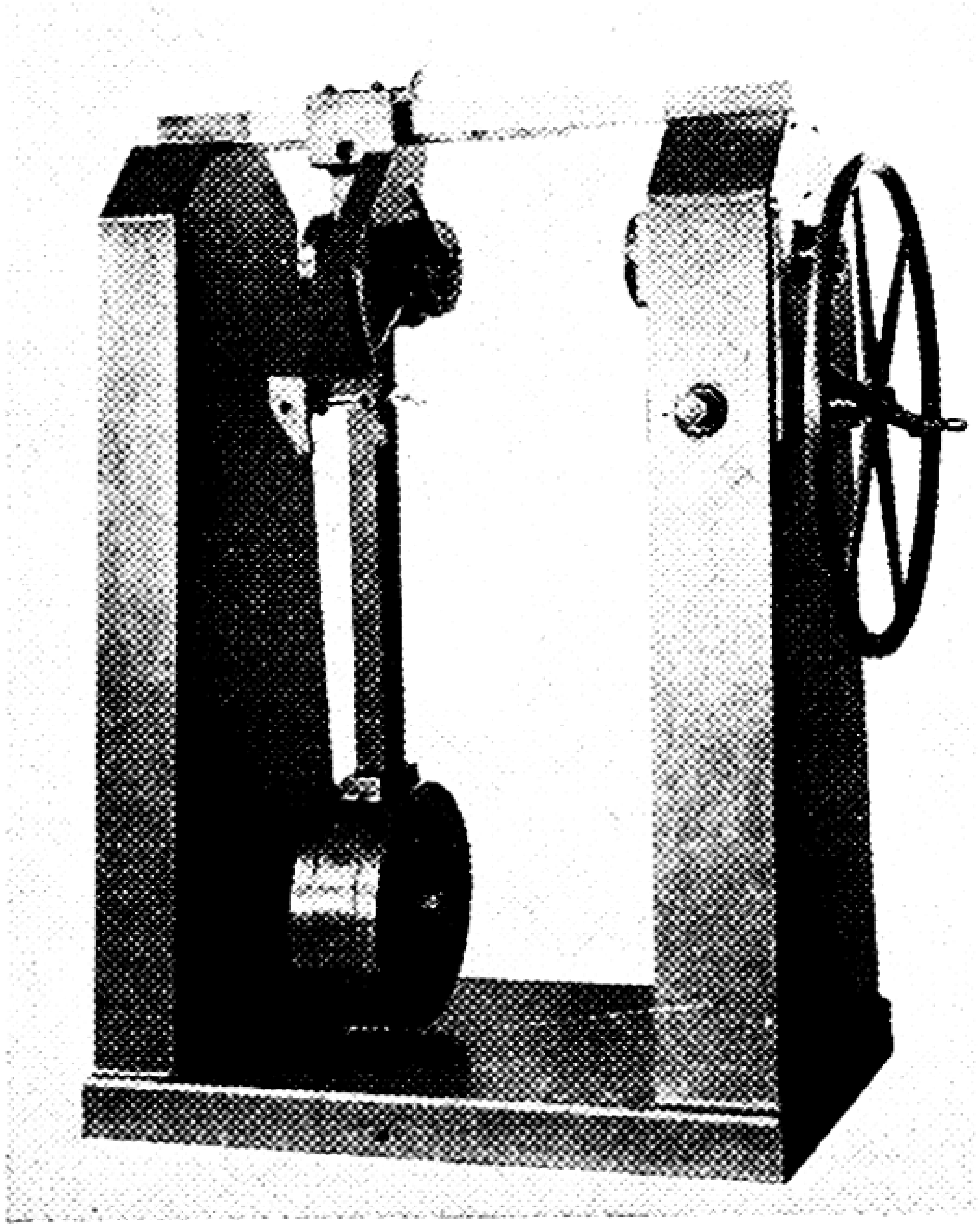


Fig. 14-9. Torsion testing machine—pendulum indicator type—capacity 10,000 inch pounds. *Courtesy Riehle Testing Machines Division, American Machine and Metals, Inc.*

A great variety of tensile testing machines is available, ranging from the small hand-operated testing machine, such as Fig. 14-6, to the huge

600,000-pound hydraulic machines. The dials on the hydraulic machines may be pressure gages connected directly to the oil cylinder, or they may be actuated by the motion of a dead-weight pendulum which is swung out by the oil pressure. The latter method, shown in Figs. 14-7 and 14-8, is the more accurate. Some of the older-type machines use a balancing beam, but readings are harder to obtain while the machine is in motion.

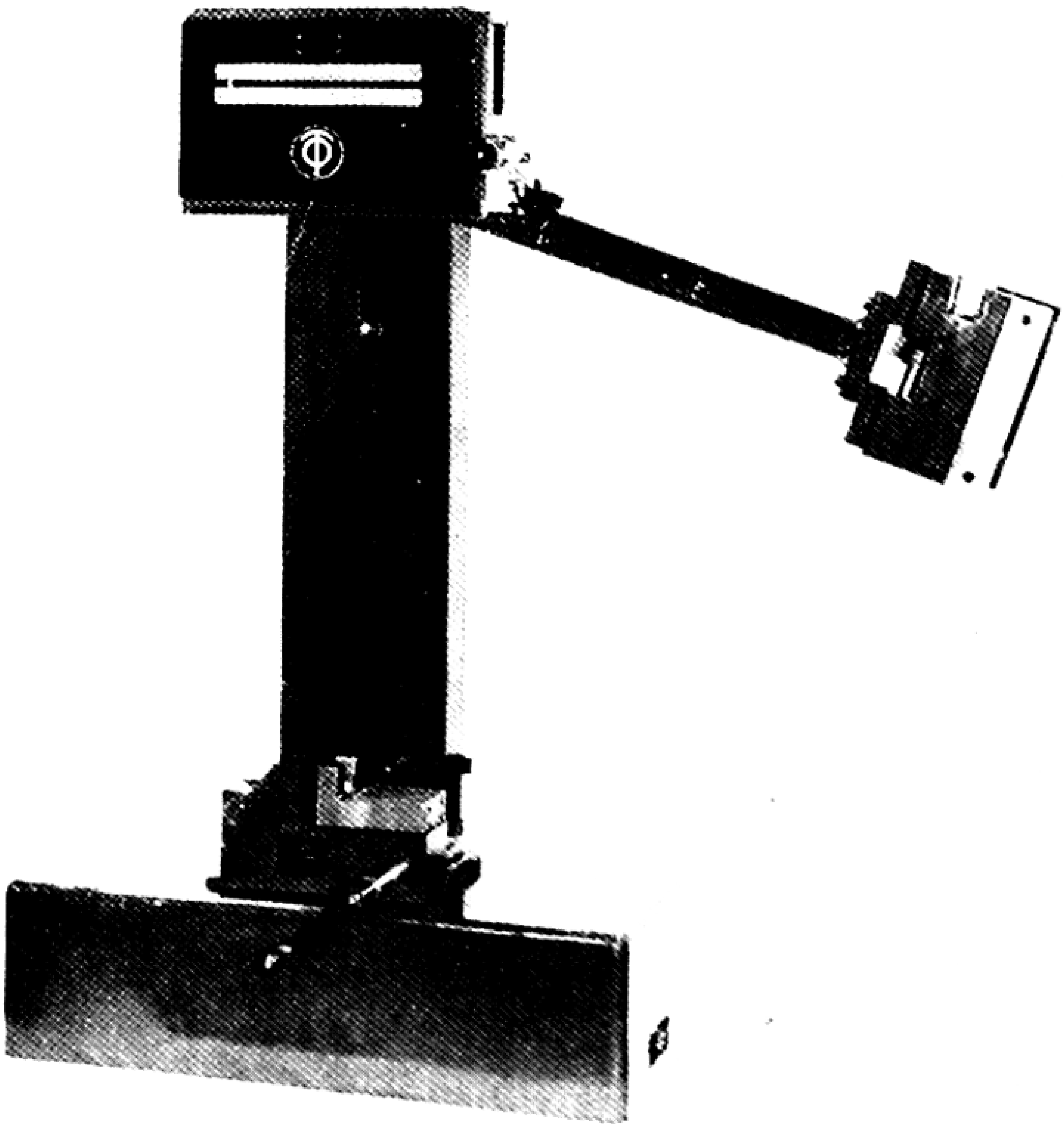
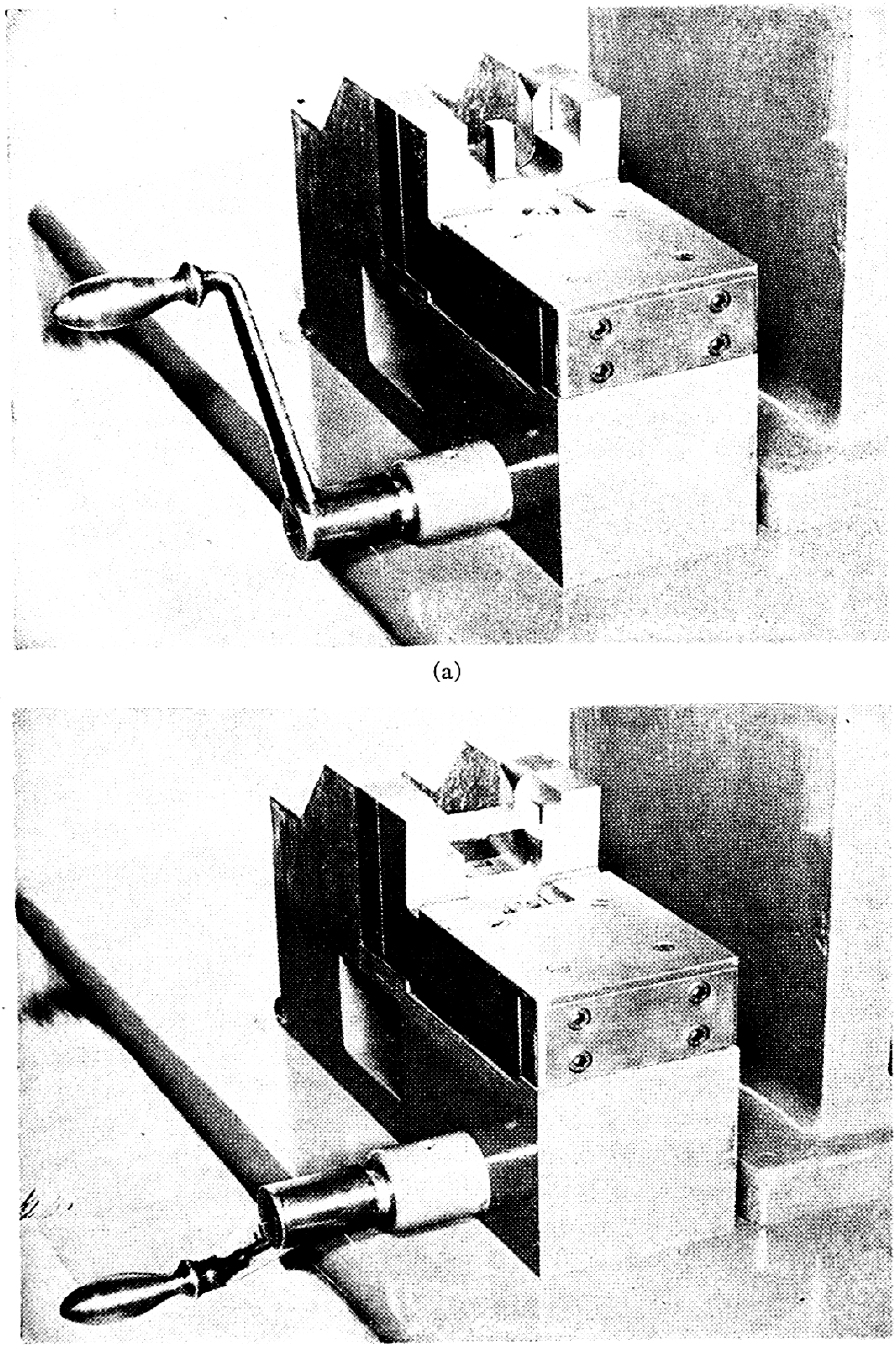


Fig. 14-10. Impact tester. *Courtesy Tinius Olsen Testing Machine Co.*

Torsion test. The torsion tester (Fig. 14-9) measures the angle of twist for a given torque in a test specimen. These data can in turn be used to determine the modulus of rigidity and the shear stress of a metal.

Impact test. The impact test is a test to show the resistance of a metal to shock. Several shapes of impact specimens are used to indicate the resistance under bending, shear, and tension. Essentially, the impact testing machine is a pendulum (Fig. 14-10) which swings freely through an arc if no test specimen is placed in the vise or fixture. The specimen is placed at the low point of the swing so that the energy of the pendulum as it strikes the specimen is measured by the height from which it started the swing. The height to which the pendulum swings after the impact is then measured. The difference between these two heights is the energy used up in breaking the specimen. This absorbed energy is a measure of



(a)

(b)

Fig. 14-11. (a) Izod fixture. (b) Charpy fixture. *Courtesy Tinius Olsen Testing Machine Co.*

the brittleness or toughness of a metal. If the metal is brittle, it snaps with the use of little energy, but if it is tough, the pendulum is in contact with the specimen for a longer period of time and thus more energy is used.

The two common types of impact tests are the *Izod* and the *Charpy tests*. The Charpy test specimen is a simple beam; the Izod is a cantilever beam. Figure 14-11 shows these specimens in the fixtures.

Fatigue tests. Applications of metals such as crankshafts, cylinder-head studs, and springs which are under repeated stresses require a knowledge of the highest stress at which the metal will withstand 10,000,000 or more reversals of stress. This stress is called the *endurance* or *fatigue limit.* There are many types of fatigue testing machines for testing rods, wires, flat metal, and springs, which produce the stress at a rapid rate.

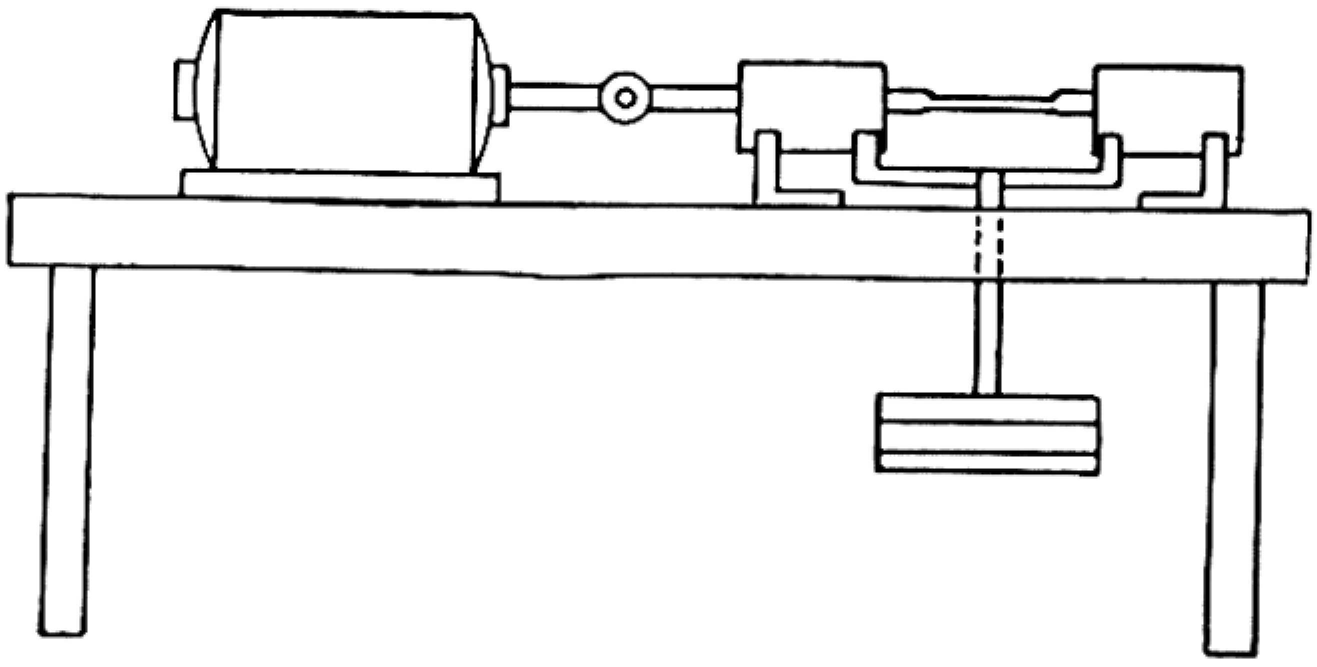


Fig. 14-12. Rotating beam fatigue tester.

The rotating simple-beam type of fatigue tester is shown in Fig. 14-12. The weights produce a bending moment in the beam which in turn produces a stress throughout the beam. This stress is a maximum in the extreme fiber (on surface). Another rotating type uses a cantilever beam. Flat test pieces have one end fastened in a vise and the other attached to an eccentric which bends the specimen. The length, cross section, and amount of bend determine the maximum stress.

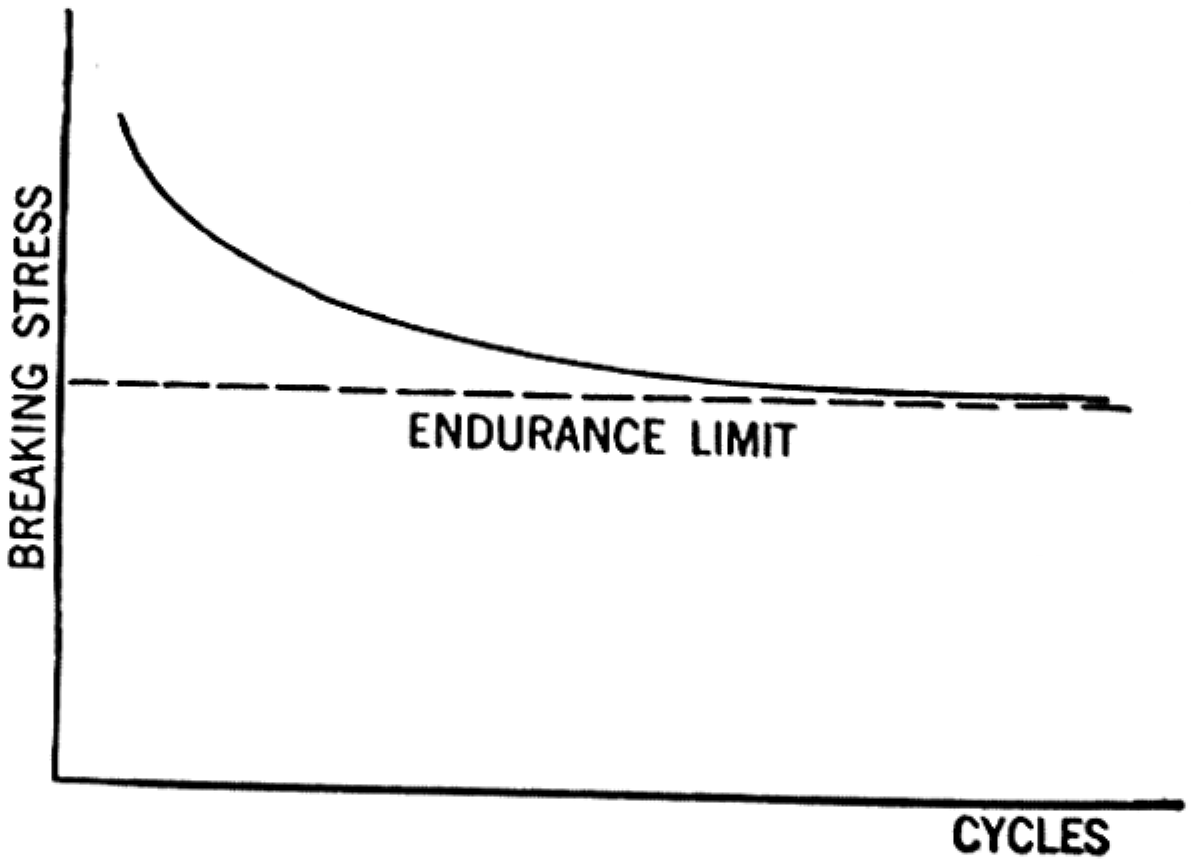


Fig. 14-13. Endurance curve.

To determine the fatigue limit, several similar specimens are tested at varying stresses. A stress is found at which one will break, then the stress on each succeeding specimen is reduced until a stress is found below which the specimen will not fracture at less than 10,000,000 reversals of stress, and over which it will fracture. The usual practice is to plot the stress as ordinate and the number of cycles as abscissa on semi-logarithm paper, as shown in Fig. 14-13. Great care must be employed in finishing the surface of fatigue test specimens, since a small surface scratch may affect the results by as much as 20%.

Creep test. The development of high-temperature steam systems and of jet engines for airplanes increased the need for a knowledge of the effect of temperature and time upon the slow elongation of metals under stress. Many factors affect the rate and amount of creep. Among them are: manufacturing process, chemical composition, heat treatment, grain size, and duration of test. The list indicates that creep can be a somewhat controlled property if sufficient knowledge is available. Creep tests require thousands of hours per test.

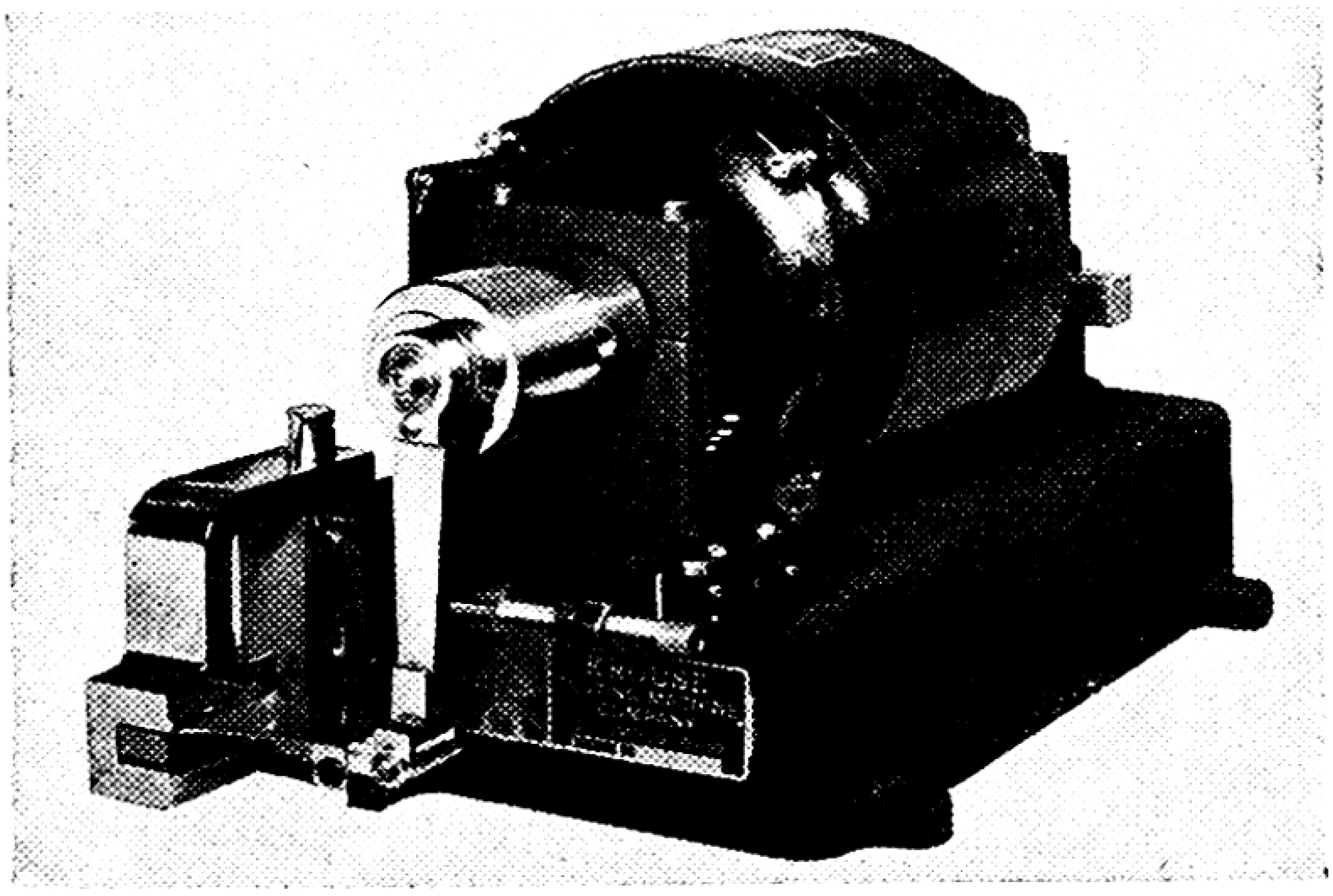
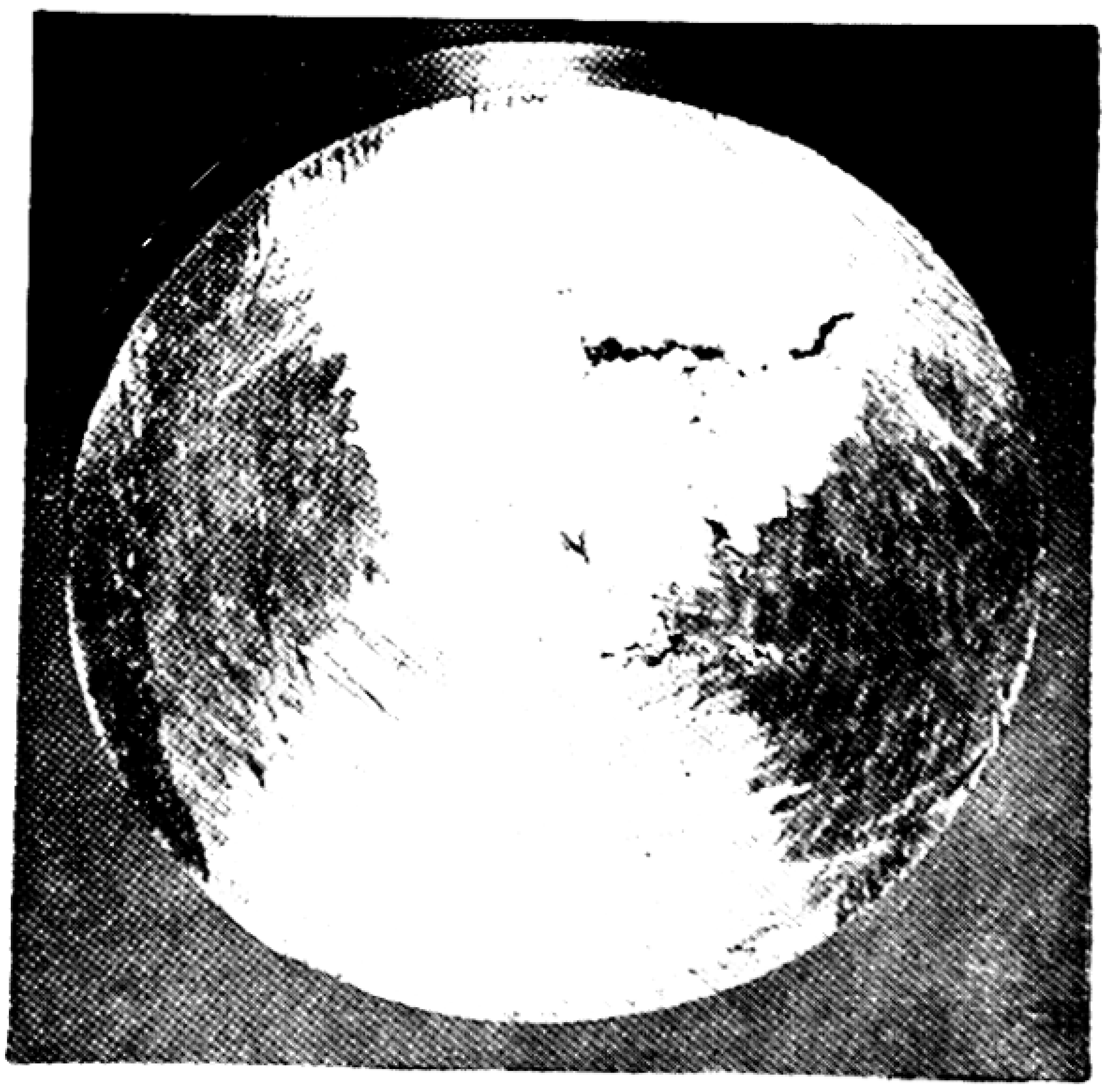


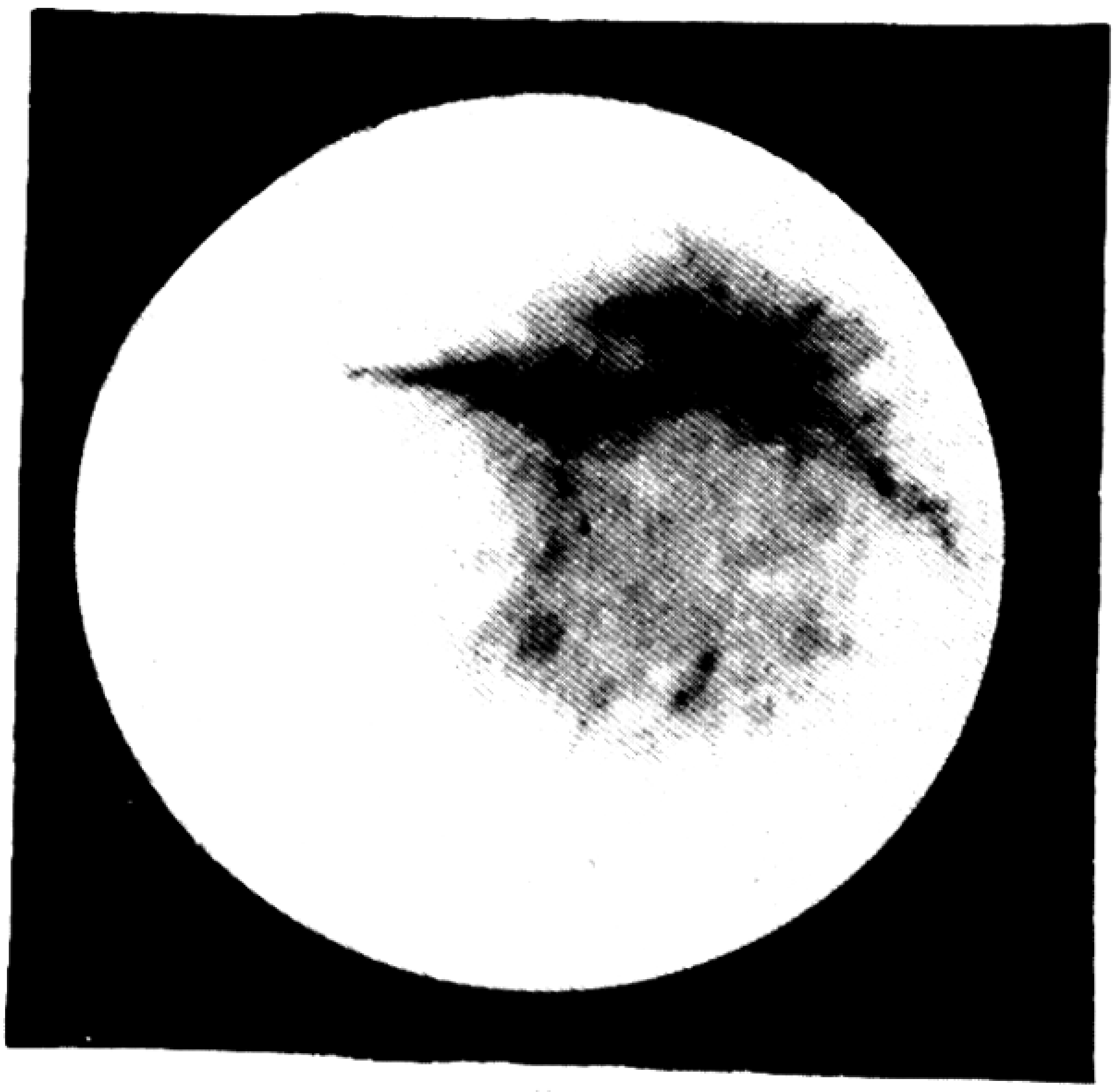
Fig. 14-14. Sheet-metal fatigue tester. *Courtesy Krouse Testing Machine Company.*

Magnaflux. This test is a method of detecting surface and subsurface flaws in magnetic materials without destroying the test piece. It is used for routine inspection of airplane and automobile parts, where a flaw might have serious consequences. The part to be inspected is flooded with oil in which fine iron filings are in suspension. Then a high magnetic flux is passed through the piece. Wherever a flaw exists, the iron filings will collect in an effort to make the magnetic path easier. These filings appear as a dark mark to indicate the flaw. The parts may have to be passed through a demagnetizing coil if they have any residual magnetism.

Radiography. X-rays, which emanate from a target bombarded by high-speed electrons, and the shorter wave-length gamma rays, which emanate from radio-active materials, have very high penetrating powers. This penetrating power is used in the inspection of metals for interior flaws. If a permanent record is wanted, the rays are passed through the work-piece, and then are permitted to strike a light-sensitive film or paper. Since the length of path within the material and the kind of material affect the strength of the ray as it leaves the work-piece, the film will indicate any change in the kind and thickness of the material.



(a)



(b)

Fig. 14-15. (a) Cross section of shrinkage area. (b) Radiograph of same section showing more information than appears in (a). *Photographs through courtesy General Electric X-Ray Corp.*

It follows that inclusions and flaws will show up on the film as is shown in Fig. 14-15.

For high-production X-ray inspection work, the parts can be passed between the X-ray tube and a fluoroscope on a conveyer. The fluroscope provides visual inspection as the image moves across the screen.

Since radium or other radio-active material emits gamma rays which are very penetrating, such materials can be used on thicker work-pieces than is possible with the X-ray. The process of obtaining a film is somewhat the same as that used with the X-ray. Radio-active material is costly and the supply is limited, hence many users lease small quantities when it is needed.

The use of radiology requires special precautions such as lead-lined rooms and remote control apparatus, since the rays break down the white corpuscles of the blood. Too much exposure to the rays can prove fatal.

Supersonic inspection. A lately developed method of inspection for flaws uses supersonic waves. A very high-frequency sound wave is projected into the test piece. At points where a flaw or an outer surface exists, a wave will be reflected. If the speed of the wave and the time for it to return are known, then the distance to the reflecting surface can be determined. The speed of the wave depends upon the material, and the time can be determined by suitable instruments. Figure 14-16 shows how a vibrating quartz crystal sends a sound beam into the test piece and picks up the reflected ray. The frequency of the sound varies from 500,000 to 12,000,000 cycles per second.

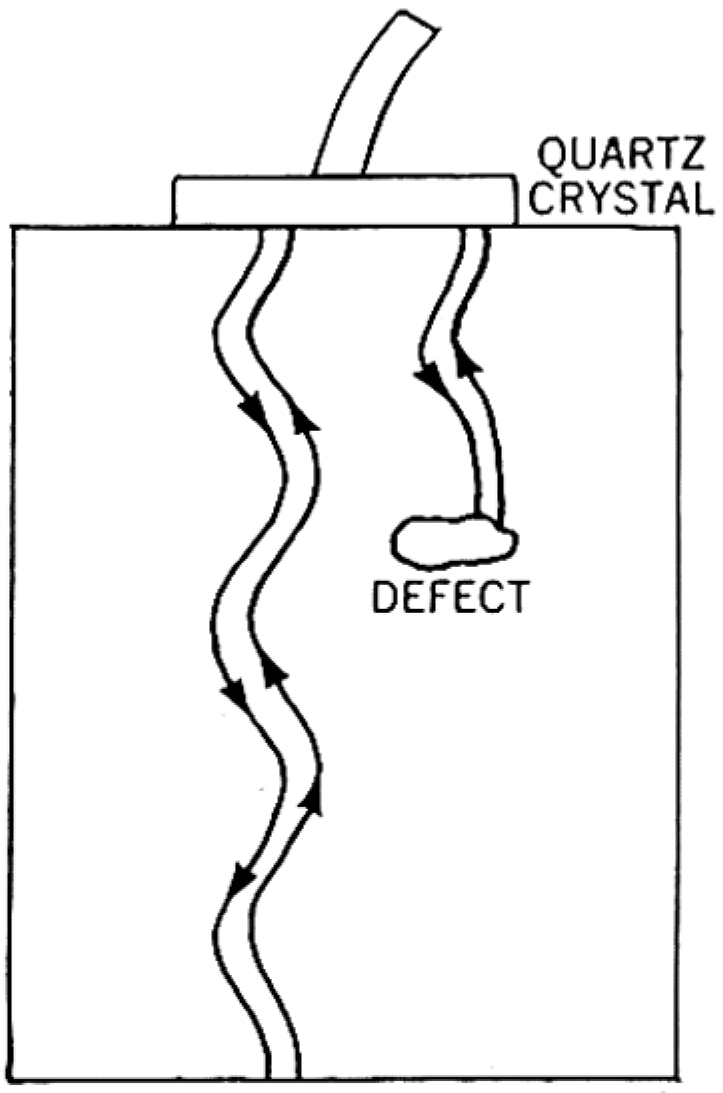


Fig. 14-16. Path of wave reflected from defect is shorter than that from opposite side.

Magnetic analysis. Composition, heat-treatment, thickness of case, flaws, and inclusions all affect the magnetic properties of steel. This fact is used in several makes of equipment for high-speed-production inspection operations. Essentially, the apparatus consists of two similar coils into which specimens known to be good are placed and through which an alternating current is passed. An instrument is then electrically connected between the two coils and adjusted to show a balance. One of the good specimens is then replaced by the work to be inspected. If the instrument shows unbalance over a specified amount, the part is rejected as being too different from the acceptable part.

This method provides a very rapid inspection method but it does not indicate the cause of the rejection.

Spectrographic analysis. The spectrograph provides a rapid means for both qualitative and quantitative analysis of metals. It is generally used as a preliminary step to chemical analysis, since it shows the elements present and their approximate percentages. Qualitatively, it is more accurate than chemical analysis for small percentages.

The method is based on the fact that every element, when vaporized by heat or electric spark, emits light that has the definite combination of wave lengths characteristic of that element. Light, as it passes through a prism or a diffraction grating, bends through angles which depend upon the wave length of the light. Thus it is possible to separate the characteristic colors. If the refracted light then hits a photographic plate (Fig. 14-17), lines will show up at the light concentrations. The distance between these lines and their relative positions indicates their wave lengths.

When quantitative work is being done, the control of the exposure time, the developing conditions, and the arc must be very close, since a comparison method is used. The quantity is determined by comparing the optical density of the lines of each element with the density of a film of a known specimen. The smaller the percentage, the weaker the line.

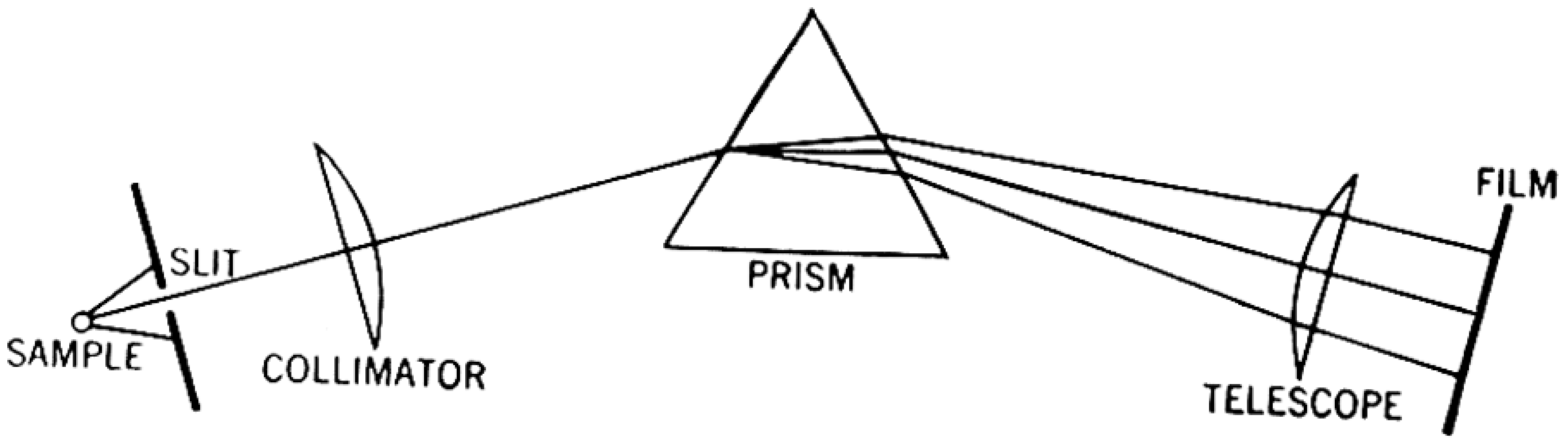


Fig. 14-17. The essential parts of a prism spectograph.

X-ray diffraction. This is a method of analyzing crystals on the basis of the arrangement of the atoms and molecules and the distances between them. Since X-rays have short wave lengths compared to atomic spacings, and since they affect photographic films, they may be used to investigate submicroscopic particles. Many properties of a metal depend upon the arrangement and the distances between the molecules and atoms. Therefore, a determination of these items can help to predict properties and to explain the existing properties.

The analysis consists of directing a beam of X-rays into a sample where some rays are reflected from successive layers of atoms beneath the surface as well as from the surface layer. If the sample is thin, other rays may pass all the way through. The rays affected by the sample then fall upon a photographic film and produce a definite pattern of lines or points. These patterns can be analyzed to gain the desired information.

Analysis of residual stress. The determination of the presence and the magnitude of residual stresses in metals is of great importance in cast and heat-treated parts. Two general methods are in use. In one, the change in the distance between two points is measured as the stress is relieved; in the other, small sections of the metal are cut free and allowed to bend to relieve the stress.

The change in distance can be measured by means of special *extensometers* or by *wire-strain gages*, and the stress is relieved either by cutting away the surrounding material or by annealing. The stress can be figured by using the relationship:

$$\text{Modulus of elasticity} = \frac{\text{unit stress}}{\text{unit strain}}$$

In the second method, the stress can be determined by figuring the stress in the metal if the small piece were bent back to its original position.

SUMMARY AND DEFINITIONS

Hardness is, in general, determined by indentation under specified loads or by resilience.

Tensile tests give the tensile strength, the yield strength, the modulus of elasticity, breaking stress, elastic limit, reduction of area, and the percentage elongation.

Torsion tests determine the shear stress.

Impact tests determine the toughness of a metal as indicated by the energy absorbed upon impact.

Fatigue tests determine the ability of a metal to withstand repeated stresses.

Creep tests show the behavior of a metal when under stress at high temperatures.

Magnaflux tests locate flaws in a magnetic metal without destroying the part.

Radiography is the taking of pictures of X- or gamma rays after they have passed through the work-piece. Since the density of the silver on the film is affected by the thickness and the density of the metal, flaws may be detected.

Supersonic inspection is used to locate flaws by means of reflected high-frequency sound waves.

Magnetic analysis compares the magnetic properties of a known piece with those of the test piece.

X-ray diffraction determines grain structure by means of the pattern of diffracted X-rays.

Spectrographic analysis makes use of the fact that each element emits light of definite wave lengths when luminous in a vapor state.

PROBLEMS

1. Compare the different methods of hardness testing. Under what conditions can each be used to best advantage?

2. What properties can be determined in a tensile test?

3. Why is it necessary to specify all the conditions under which a test is made?

4. What is the main difference between Izod and Charpy impact tests?

5. Under what conditions would the endurance limit be the limiting stress?

6. When would creep tests be important?

7. What precautions are necessary in radiographic work? Why?

8. What is the difference between X-ray and gamma ray radiography?

9. Explain how sound is used in the detection of flaws.

10. What are the advantages of X-ray diffraction over other methods of analyzing metals?

11. What fact is spectrographic analysis based upon?

Chapter 15

METALLOGRAPHIC INSPECTION

Many times metallographic inspection is the only method by which the properties of a metal can be explained. It can show grain size and shape, inclusions and segregations, and other factors which govern the physical characteristics of metals. This chapter describes the laboratory processes and the equipment used in macro- and micro-examination.

The steps in both types of investigation are:

(1) Obtain sample.
(2) Polish sample.
(3) Etch sample.
(4) Inspect sample with proper magnification.
(5) Photograph sample if a permanent record is desired.

Macro-inspection is inspection by the naked eye or by magnification up to 10X; micro-inspection uses magnifications beyond 10X.

Obtaining samples. After determining the purpose of the investigation, the next step is to obtain a sample which illustrates the point in question. If the purpose is to investigate a failure, samples should be taken not only near the failure, but also far enough away to show the character of the sound metal.

Specimens of heat-treated metals should include some surface metal so that the effects of decarburization, carburization, and other surface changes can be studied. In investigating for segregations, samples from many points should be obtained and should be compared as to the amounts of each constituent present. Metals having grains with directional characteristics should be studied with samples both with the grain and across the grain. This type would include cold-worked and forged metals.

Definite practical limits to the size of a specimen exist. The maximum size should be about one inch square; if it is larger, scratches are hard to eliminate, inclusions are more easily dislodged, and the time for grinding and polishing is excessive. A specimen less than one-quarter inch in diameter is difficult to polish without rounding the edges, especially when it is polished unmounted. Mounted specimens may be smaller.

The method of obtaining the sample piece from the parent metal depends somewhat upon the size of the parent metal and the location of the sample. Regardless of the method of obtaining the sample, the metal must not be dragged or heated. Dragging rearranges the crystals and inclusions, and heating may change the crystal structure. Samples can be cut away by a well-lubricated hacksaw, a cutoff machine, or, away from the edge, by flame-cutting. Since flame-cutting heats the metal excessively, a large piece should be cut by flame and then trimmed to size by a hacksaw or preferably by a cutoff while submerged in water. The cutoff wheel not only cuts a flat surface but also eliminates the necessity for rough grinding. A cutoff machine is shown in Fig. 15-1.

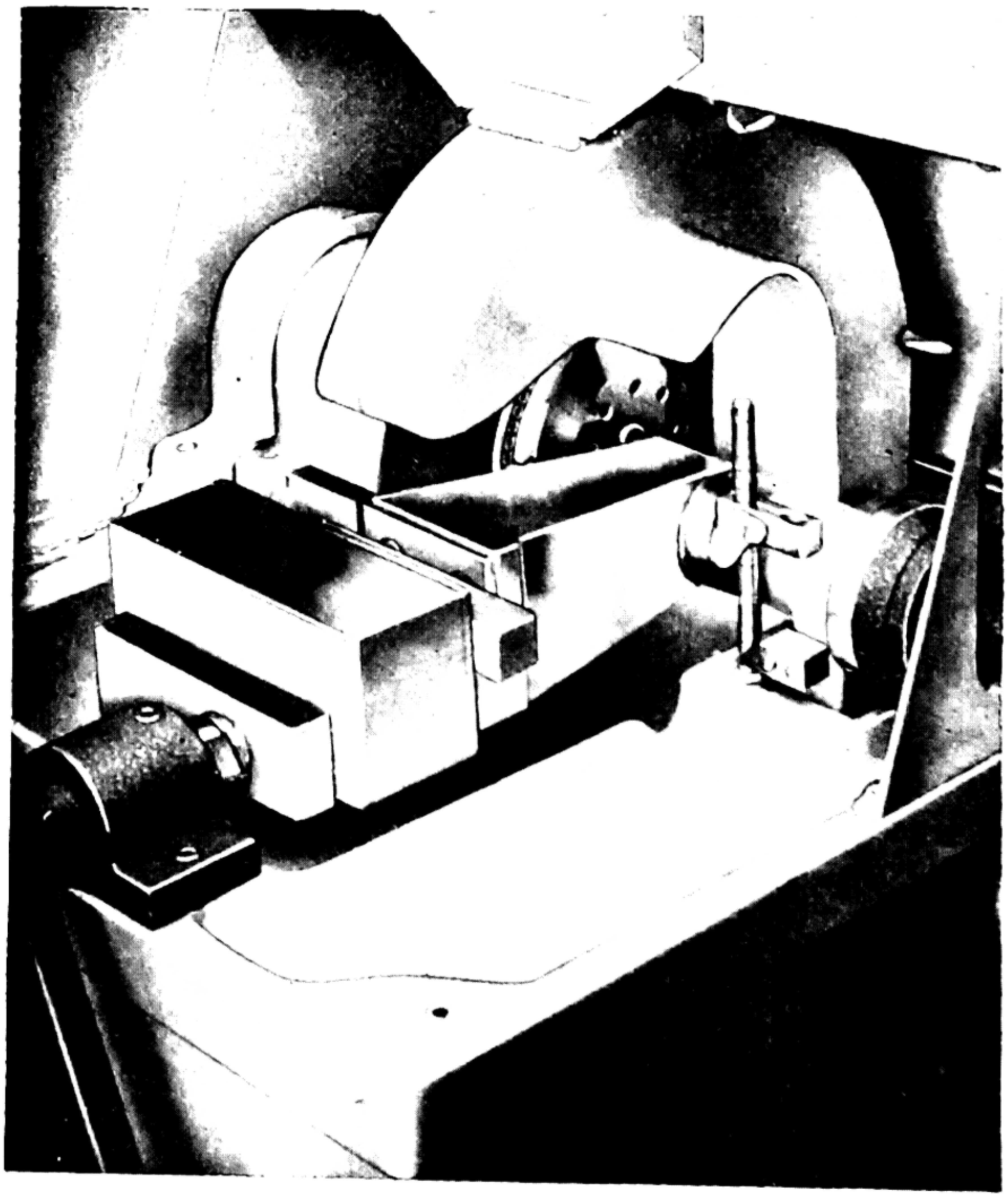


Fig. 15-1. Submerged cutoff machine showing vise in loading position. Vise lowers under coolant. *Courtesy Precision Scientific Company.*

Mounting specimens. Although certain types of specimens can be polished unmounted, the best results are obtained when they are mounted. Irregularly shaped pieces such as screws can be successfully polished when mounted in plastics. The mountings tend to prevent rounding of the edges and give the necessary flat surface.

Included among the several mounting materials are soft metals, Bakelite, Lucite, and Tenite. The hard plastics are easy to mold, and do not smear the specimen as do the soft metals. Bakelite is preferred to other molding compounds, but Lucite is excellent if it is desirable to see the whole specimen. Several small specimens may be placed in one mold.

Special mounting clamps have been designed which clamp the specimens firmly in place without the use of plastics. These clamps can be used for hand polishing, but they give better results in polishing machines which hold the mount level at all times.

Several plastic mounting presses on the market are nearly automatic. Figure 15-2 shows a press with a thermostat control and a fluted block for fast cooling.

If the specimen is small and the edges must be preserved, it is best to copper or nickel electroplate the surface before cutting off the sample. This plating strengthens the casing and prevents chipping.

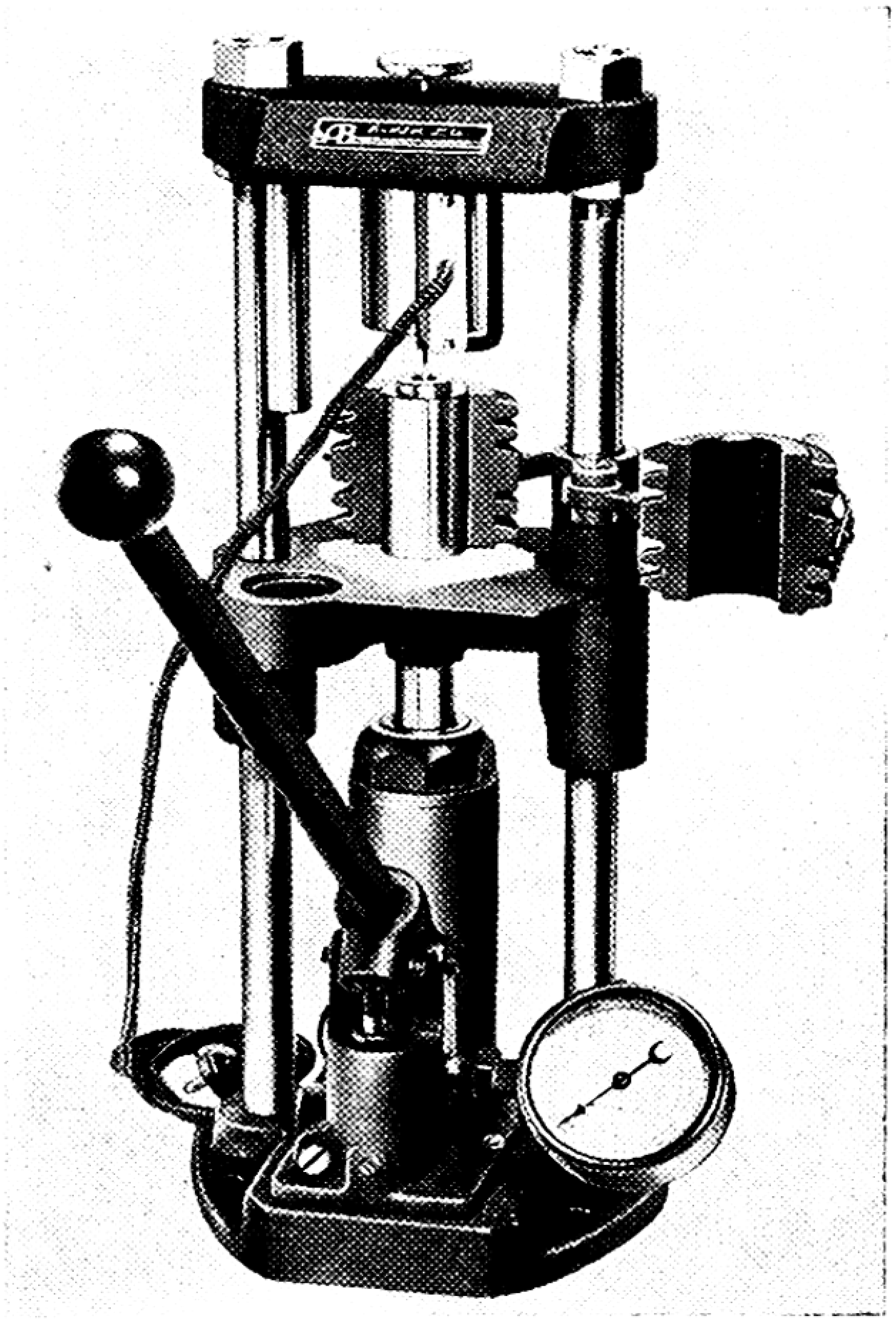


Fig. 15-2. Press for mounting specimens in plastics. *Courtesy Buehler Ltd.*

Facing. Cutoff wheels usually eliminate this step, but it is needed if a hacksaw has been used to cut the specimen. Facing is essentially a first step in obtaining a flat smooth surface. It can be done by use of a file, a facing stone, a belt grinder, or by machining. If a file is used, it is best to place the file flat on the bench and rub the specimen over the file in one direction. This arrangement tends to reduce the possibility of rounding the edges. Facing or grinding stones tend to fill up with metal quickly and to develop a wavy surface. Therefore they need frequent dressings to keep them in good order. Belt grinders have proved satisfactory if the belt is changed frequently.

Care is extremely important in facing, since overheating or scratching too deeply may alter the structure sufficiently to spoil the sample.

Grinding. The next step in the preparation of a specimen is the removal of all but the finest scratches. The surface should be left in such a condition that the final polishing steps will require a minimum of time.

In all grinding and polishing operations, clean specimens and clean hands are of the utmost importance. One piece of coarse abrasive carried over to a fine abrasive step may necessitate repeating the previous step.

Several methods of grinding specimens have been developed. A few of them will be described. The hand method requires the least amount of equipment, but it is tedious and expensive from a labor standpoint. In the hand process, emery paper is placed on a flat piece of wood, metal, or glass, and the specimen is rubbed carefully back and forth over the surface. Care must be taken not to overheat the surface by rubbing too fast and not to round the edges. Usually at least four grades of paper are used: Nos. 1, 0, 2/0, 3/0, and sometimes 4/0. When the change to a finer paper is made, the piece should be rotated 90° to make it easier to see when the scratches from the previous operation have disappeared. Scratches should never be carried over two grades of paper.

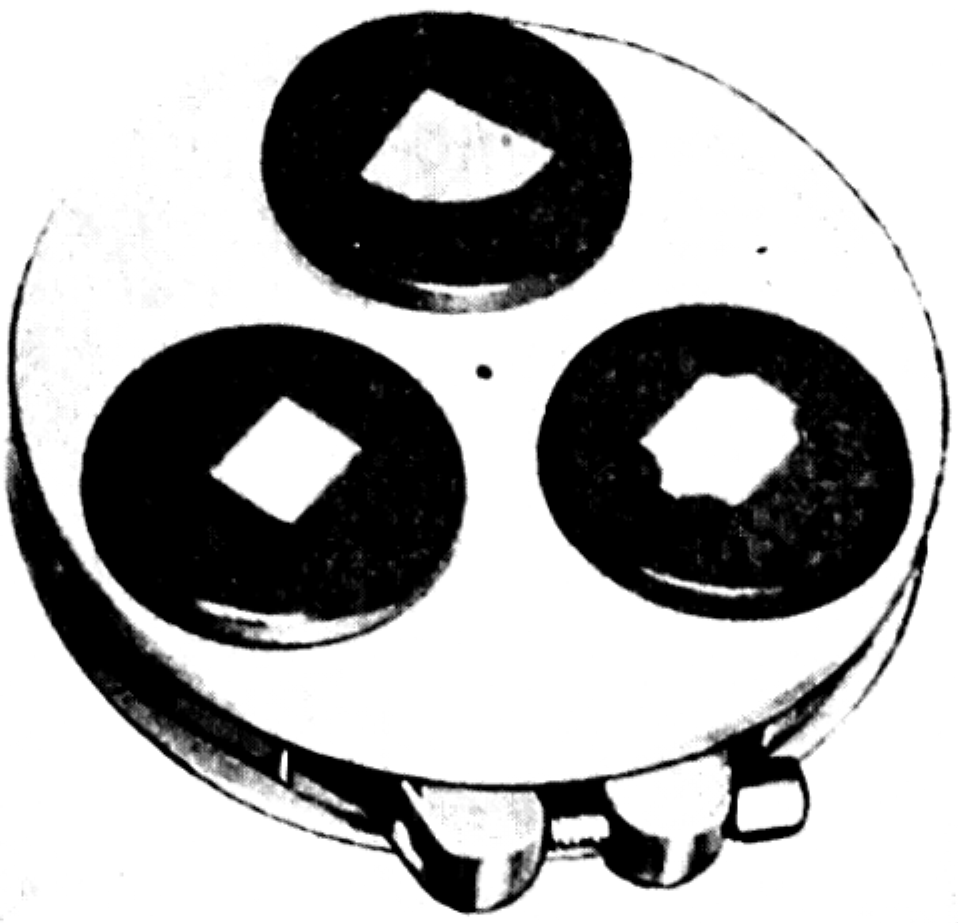


Fig. 15-3. Mounted specimens in hand polishing fixture. *Courtesy Precision Scientific Company.*

Two types of machine grinders using emery paper up to 3/0 are available. One is the belt grinder shown in Fig. 15-4; the other is a disc grinder having four grades of paper on the four sides of the Bakelite discs (Fig. 15-5). Either type is faster than hand polishing, but there is some danger of overheating the specimen. The surface speed, when a disc grinder is used, can be reduced by working near the center of the disc.

Paraffin discs are sometimes used, especially for the softer metals. Such discs are made with concentric grooves to hold the water and abrasive. The abrasive is in suspension in the water which is frequently sprinkled over the surface of the disc, and the paraffin tends to hold the abrasive in place.

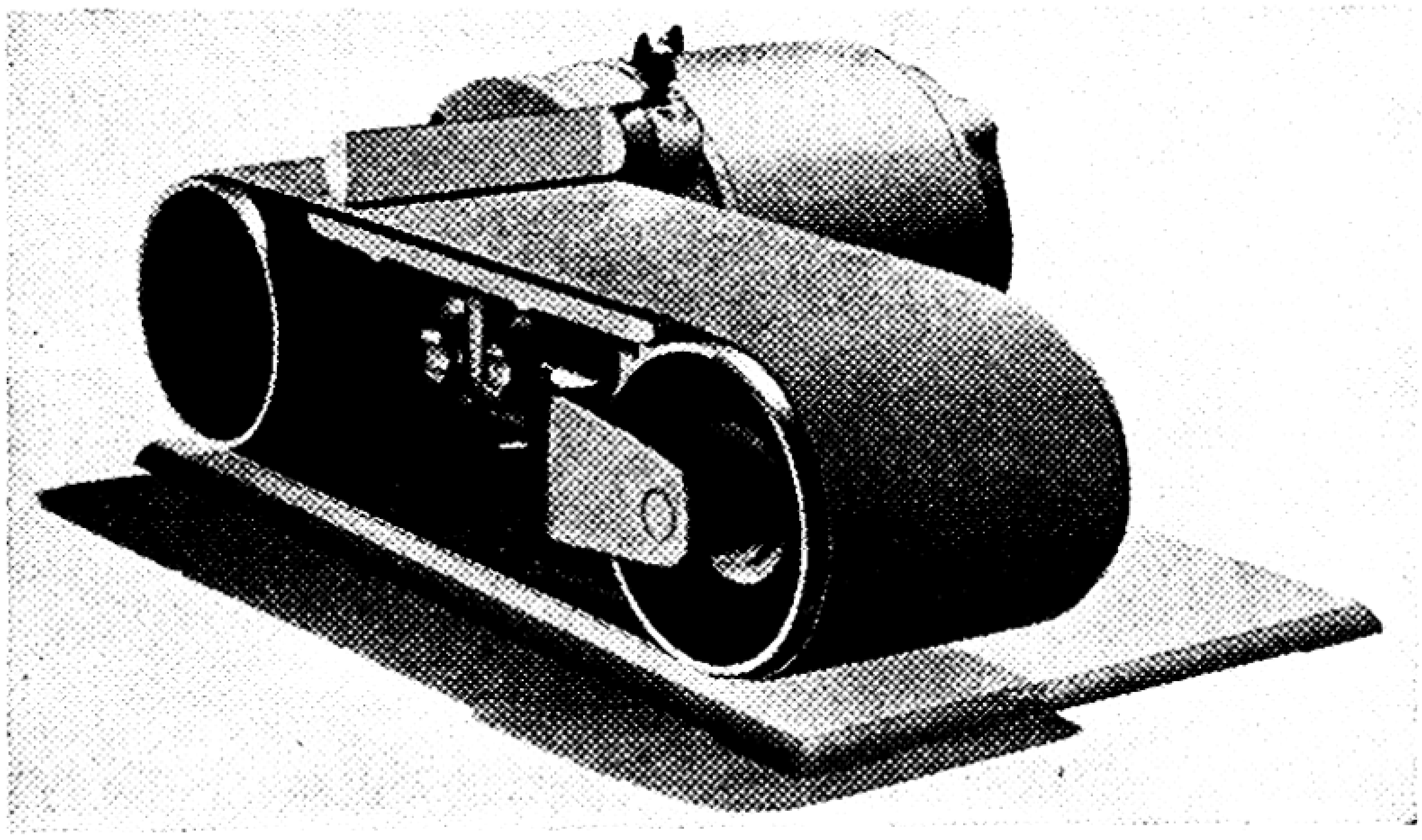


Fig. 15-4. Belt grinder. *Courtesy Buehler Ltd.*

Lead discs or laps can also be used with excellent results. The abrasive for this type is mixed with a thin, fast-drying varnish and then spread over the lap. The varnish holds the emery or tungsten carbide particles in place during the grinding operation.

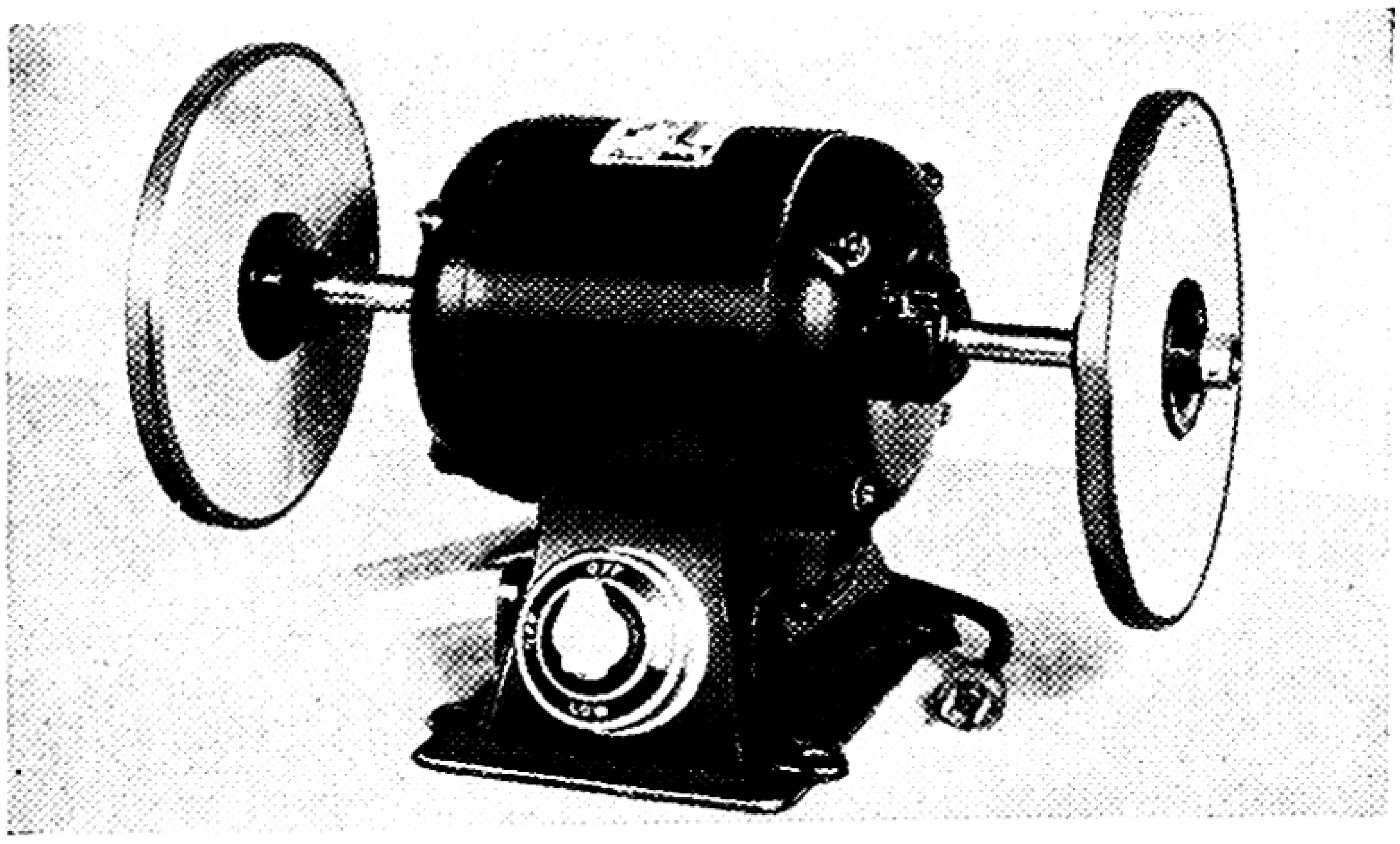


Fig. 15-5. Disc grinder using four grades of paper. *Courtesy Buehler Ltd.*

A faster and more automatic method has been developed which uses a series of about four laps in a grinding and polishing machine that can work several specimens at once. These four laps carry through to the finish polish. Figure 15-6 shows such a machine. The laps used are usually crystolon stone lap, levigated alumina stone lap, wax lap, and felt lap, although they may vary with the metals being polished.

Polishing. Polishing removes the scratches left by the grinding operations. Sometimes it is best to use a rough polishing operation before the final polish. This operation requires the use of No. 4/0 papers, or No. 600 emery, or tungsten-carbide powders. The polishing methods include:

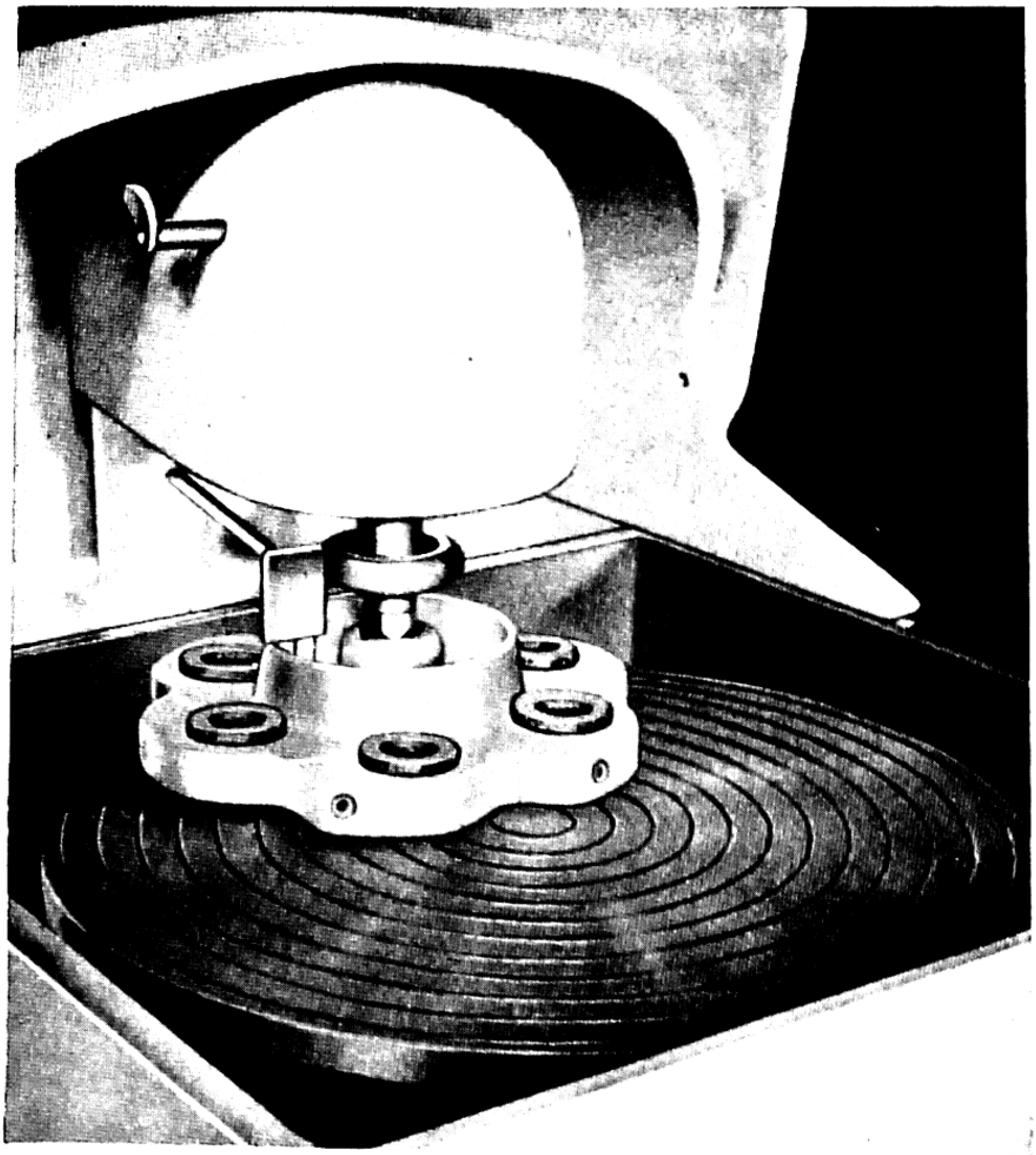


Fig. 15-6. Automatic polishing machine showing specimen holder and lap. *Courtesy Precision Scientific Company.*

(1) Dry, loose powders on billiard cloth or canvas: this method produces a good finish, but it may dislodge inclusions.

(2) Grinding papers: can be used where inclusions are being studied.

(3) Wax or paraffin laps: a good method for both the retention of inclusions and a good polish.

(4) Lead laps: this method produces a good finish, retains the inclusions, and makes a flat surface.

The speed of polishing depends upon the metal. In general, it can be said that slow polishing speeds should be used for soft metals and metals with inclusions. If only one motor speed is available, the specimen can be moved near the center of the lap for low-speed polishing, and near the edge for higher speeds.

The final polishing is done on soft cloth with very fine finishing powders, such as levigated alumina magnesia, or rouge. If the metal contains inclusions, the cloth should be the harder silk, heavy cotton, or linen, but if a high polish is desired, the softer broadcloth, "kitten's ear," or chiffon velvet are better.

Figure 15-7 shows a polishing machine with two speeds so that it can be used for both hard and soft metals.

After the final polishing operation, the specimen should be washed in alcohol and dried with a soft cloth or an air blast. Nothing should touch the polished surface, particularly one's fingers.

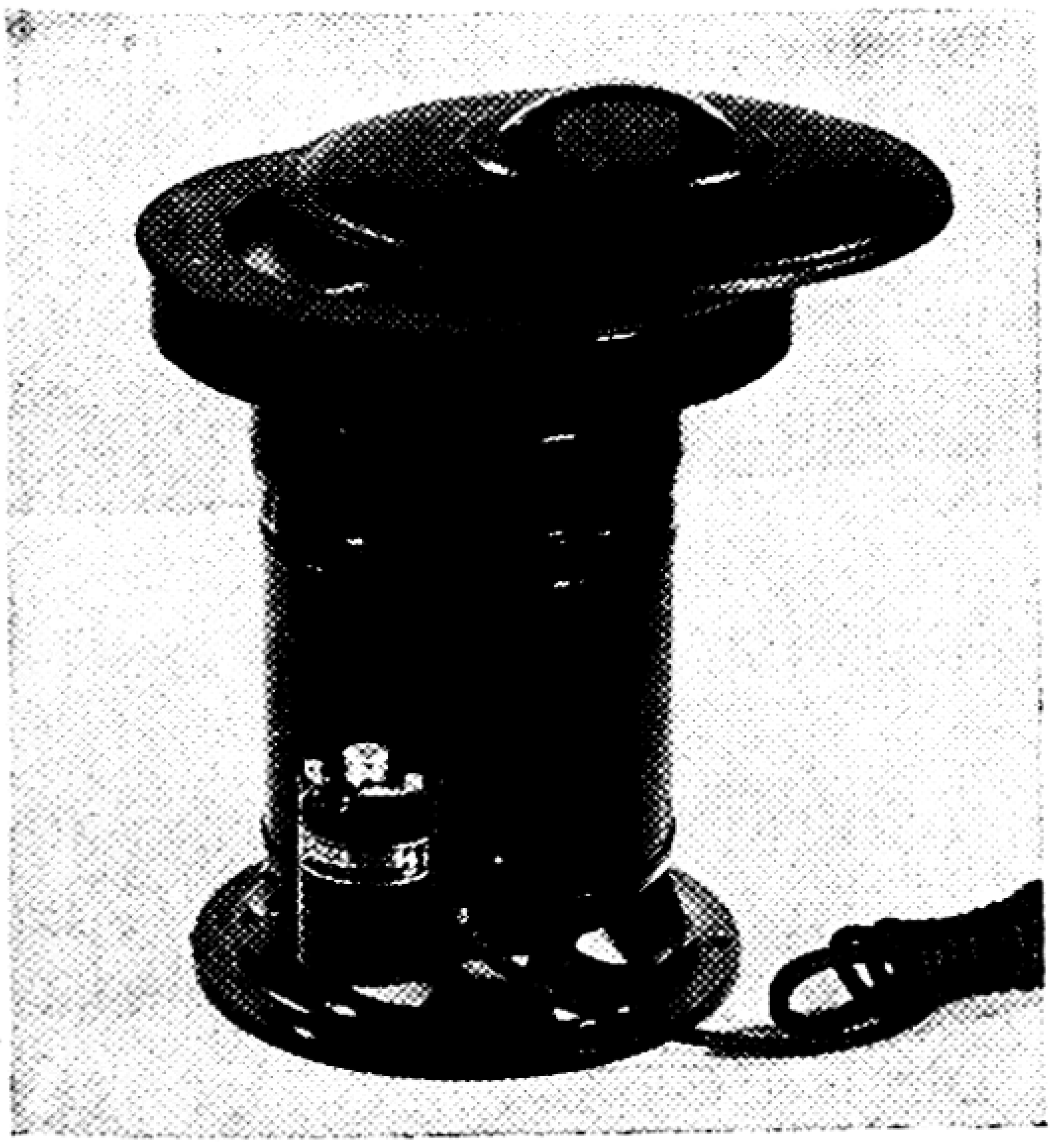


Fig. 15-7. Two-speed polisher. *Courtesy Buehler Ltd.*

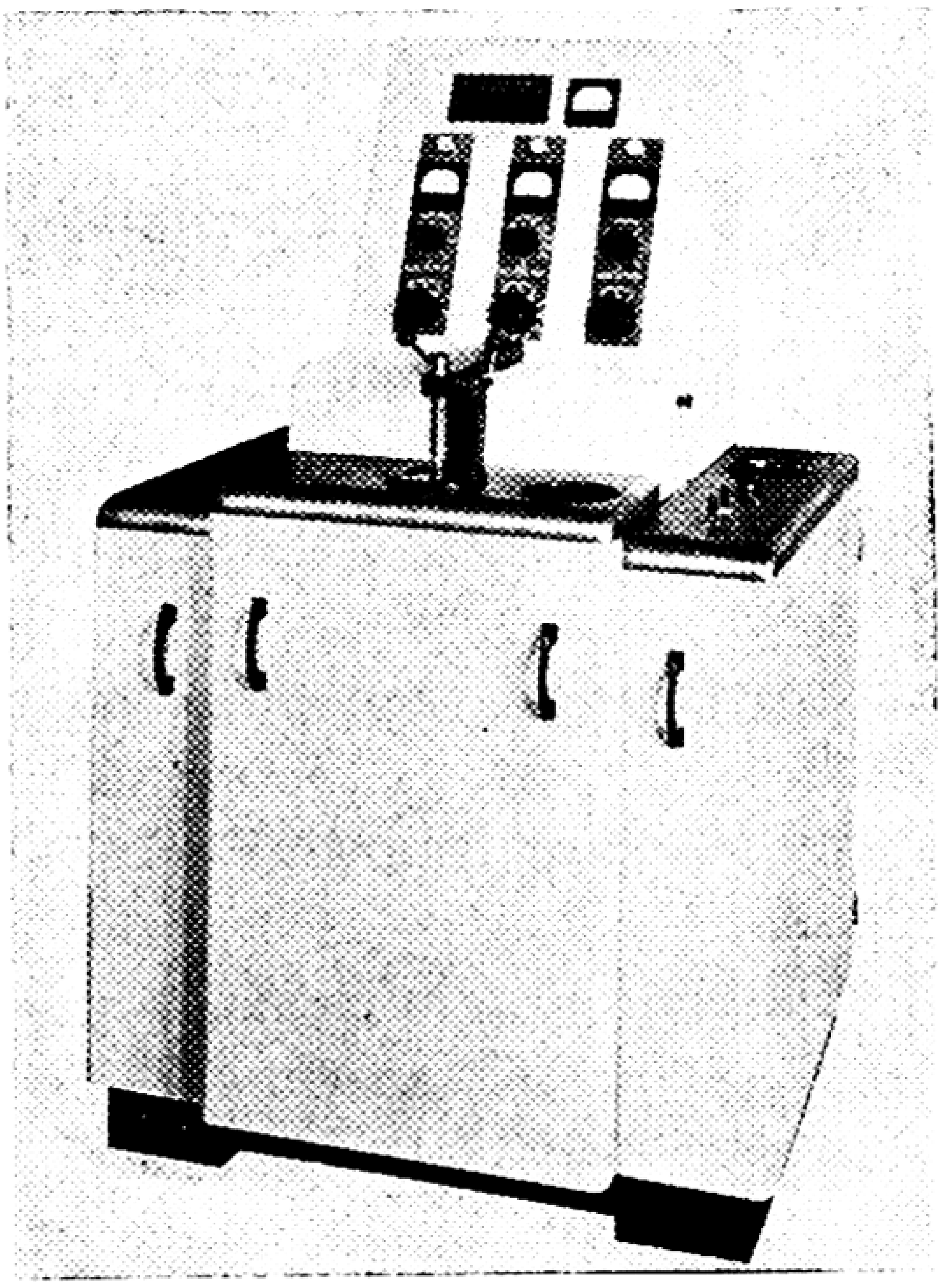


Fig. 15-8. Electro-polisher and etching machine. *Courtesy Central Scientific Co.*

Etching. In order that the different constituents may be seen through the microscope, the different constituents as well as the grain boundaries and inclusions must have contrasting appearances. The contrasts are produced by using chemical reagents which attack the various constituents at different rates and in different ways. Many etching reagents have been developed to give specific results. A list of these reagents with their applications is given in the *Metals Handbook* of the American Society of Metals.

Electrolytic etching is accomplished by using the specimen as the anode and by passing a small electric current through an electrolyte of weak acids, alkalis, or other solutions. The constituents of the specimen are attacked at different rates. Contrasting appearances are thus produced.

One electro-polisher on the market (Fig. 15-8) combines the polishing and etching operations. The specimen is prepared in the usual manner up to grinding on 2/0 or 3/0 paper. Next, it is electrolytically polished and etched, and is then ready for microscopic inspection. The operation takes about a minute.

After etching, the specimens should be thoroughly washed in alcohol and dried by air blast, soft cloth, or lens tissue. Nothing should be allowed to touch the etched surface. The surface may be protected from the atmosphere by an application of thin, transparent lacquer, although the lacquer may reduce the contrast and detail.

Microscopic inspection of specimens. In microscopic inspection, the microscope should be adjusted and the specimen illuminated to give the greatest detail.

In general, the higher the magnification of the microscope, the finer the detail that can be seen. However, limiting factors do exist. One is called *resolution*, which means the ability of the microscope to separate lines placed close together. A second factor is the *depth of focus*, which indicates how much of the depth of a rough surface can be in focus at one setting of the microscope. The depth of focus decreases as the magnification is made larger, although this aberration can be somewhat corrected by decreasing the area of the lens in actual use. This action is called "stopping it down." Distortion and resolution will be reduced at the same time.

The type of lighting has a very large effect upon the detail shown in the image of the specimen. Several types of illuminators are used: plane-glass vertical illuminator, prism vertical illuminator, conical illuminator, dark-field illuminator, and polarized light.

The *prism illuminator* is shown in Fig. 15-9. It can be seen that the prism blocks out about one half the lens. This blocking has the same effect on the resolving power as stopping down the lens, that is, it reduces the resolution. The *plane-glass illuminator* is shown in Fig. 15-10. In this type, the whole lens is used. A small amount of light from the source is reflected by the glass through the object lenses, and onto the specimen. The light reflected from the specimen then again hits the plane glass; a small part is reflected, but most of it passes through. Since the whole lens is used, the resolving properties are better than those of the prism illuminator. The plane-glass type requires a stronger light source than the prism type because only a small percentage of the source light is reflected to the specimen.

Contrast can be increased by eliminating the center rays of the light from the source by means of a small disc placed in their path. This system is called *conical illumination*. It increases the contrast by having all the rays strike the specimen at an angle.

The foregoing types of illumination are called *direct illumination* because the light strikes the specimen from the objective lens and is reflected back through the lens. In direct illumination, the matrix or background reflects light and is therefore bright. The structures have sufficient angle to cause the reflected light to miss the lens, thus making them dark.

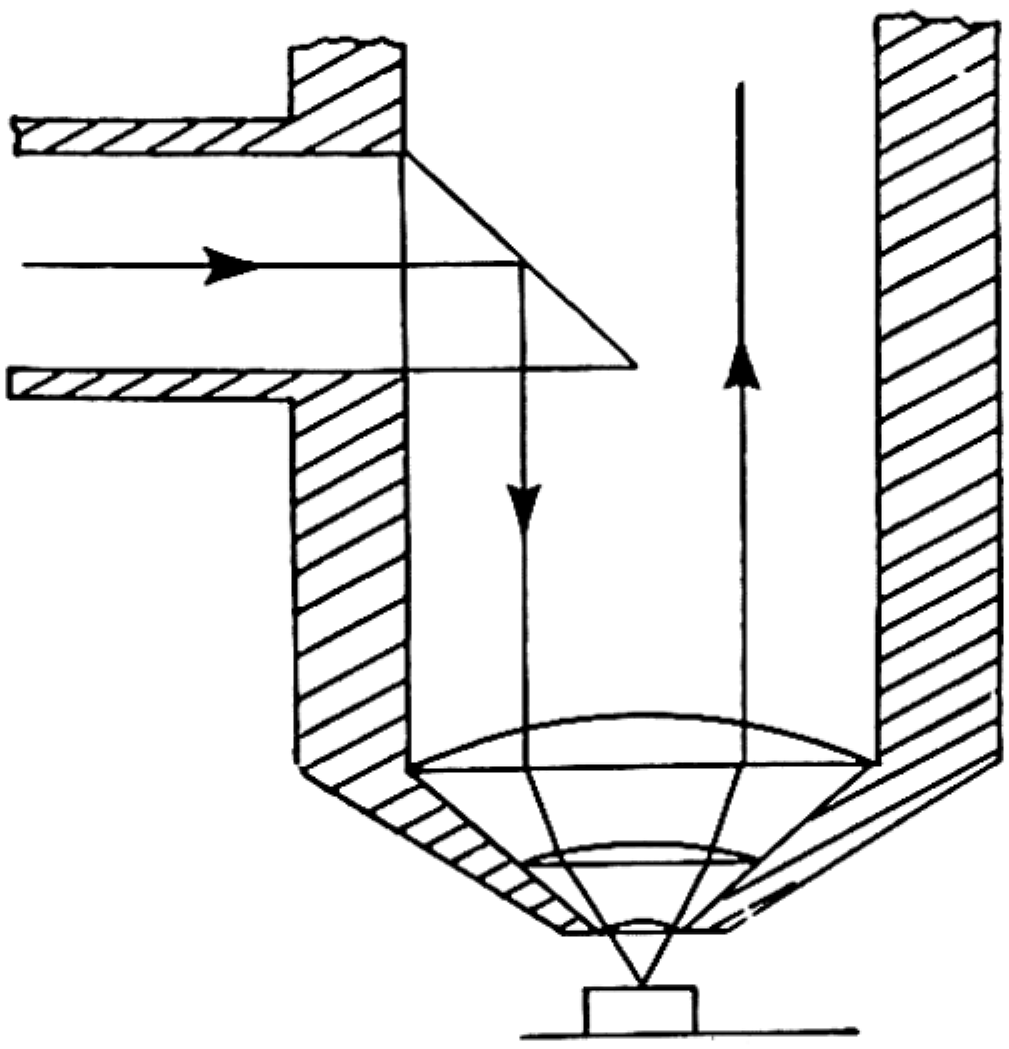


Fig. 15-9. Prism vertical illumination.

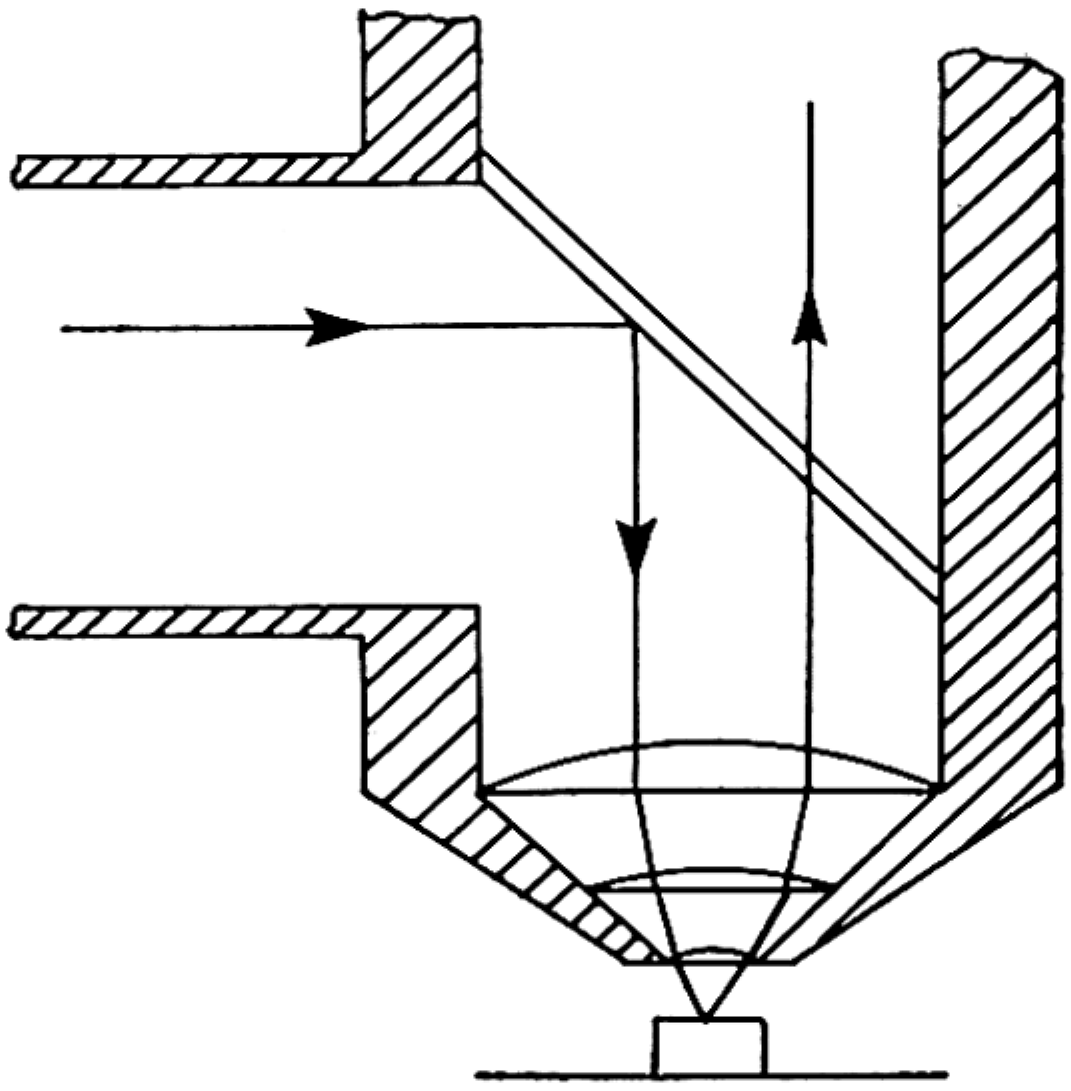
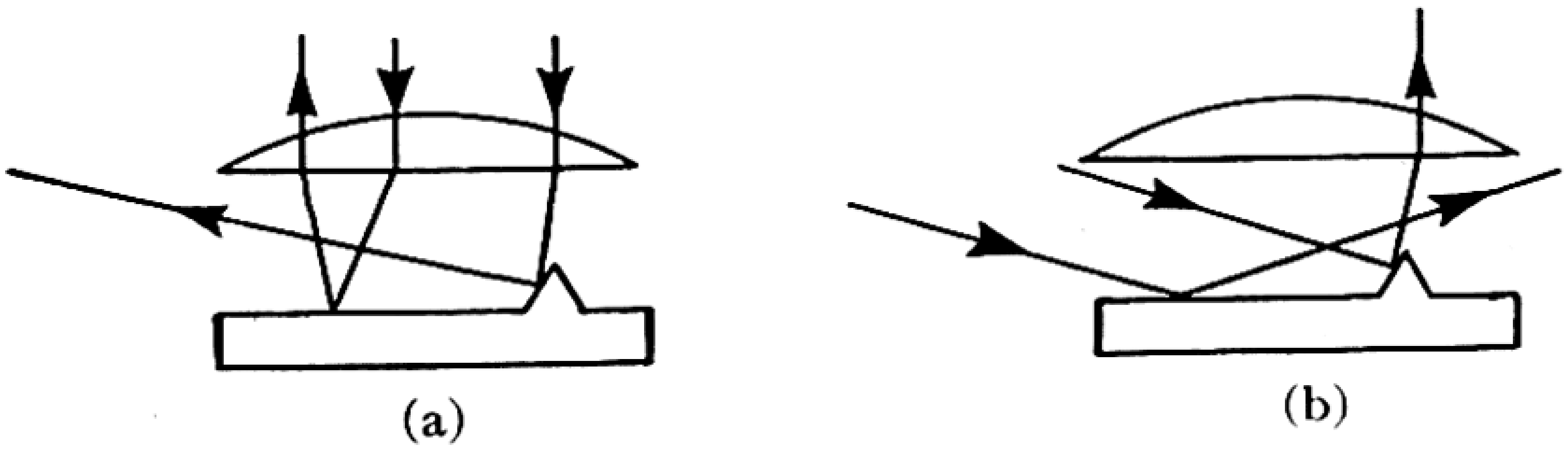


Fig. 15-10. Plane-glass vertical illumination.

Dark-field illumination is the opposite, since light strikes the specimen from an angle rather than perpendicularly, hence the background is dark and only the structures reflect light through the objective lens, as shown in Fig. 15-11.



(a)

(b)

Fig. 15-11. (a) Direct illumination. (b) Dark-field illumination.

Polarized light is used with microscopes in the identification of inclusions and constituents. It is a subject beyond the scope of this book.

Correct magnification. In general, the best results are obtained by using the lowest magnification which will show clearly the details under investigation. However, certain limits exist, both upper and lower, which depend upon the particular lenses being used. The lower limit is 400 times the numerical aperture (N.A.) of the objective, since at least that magnification is needed to make it possible to see the detail as resolved by the objective. A normal upper limit is 1000 N.A. with an achromatic lens, if a sharp image is to be retained.

Films and filters. Different types of films are most sensitive to different wave lengths (colors) of light. Since short wave lengths give the best resolution, films sensitive to short wave lengths as well as the longer wave lengths should be used. If the metal has various colors, filters which even the effect of the different wave lengths on the film should be used to give a true picture of the specimen. In other words, the filter choice is determined by the film, the specimen, and the light source. The choice of printing paper depends upon the contrast desired. Often insufficient contrast due to poor illumination can be compensated for by choosing a high-contrast paper.

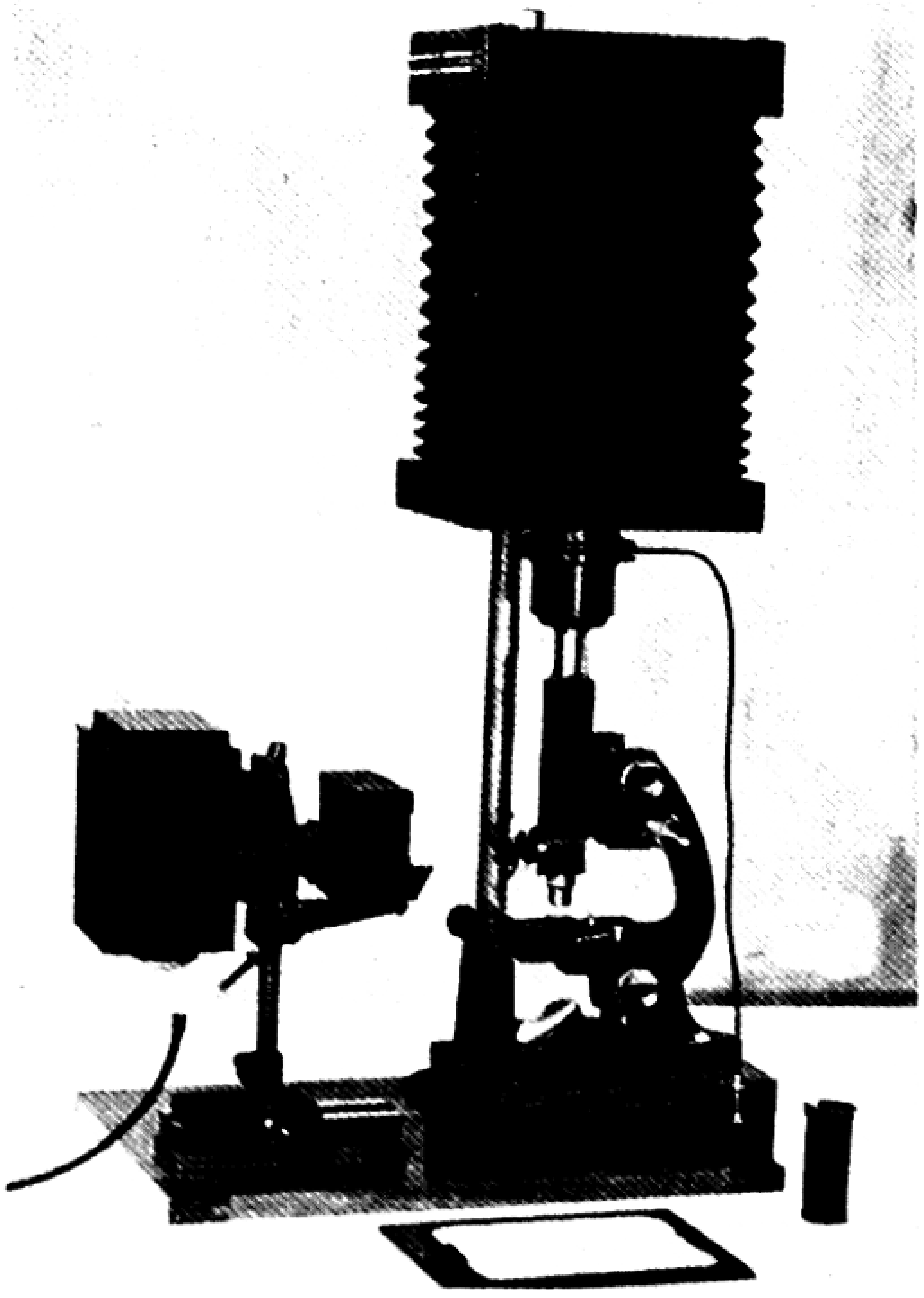


Fig. 15-12. Microscope and camera for photomicrography. *Courtesy Bausch & Lomb Optical Co.*

Microscopes. Figure 15-12 shows a microscope which can be used separately for visual examination or with the camera for photomicrographic work. For direct illumination, a vertical illumination unit must be used.

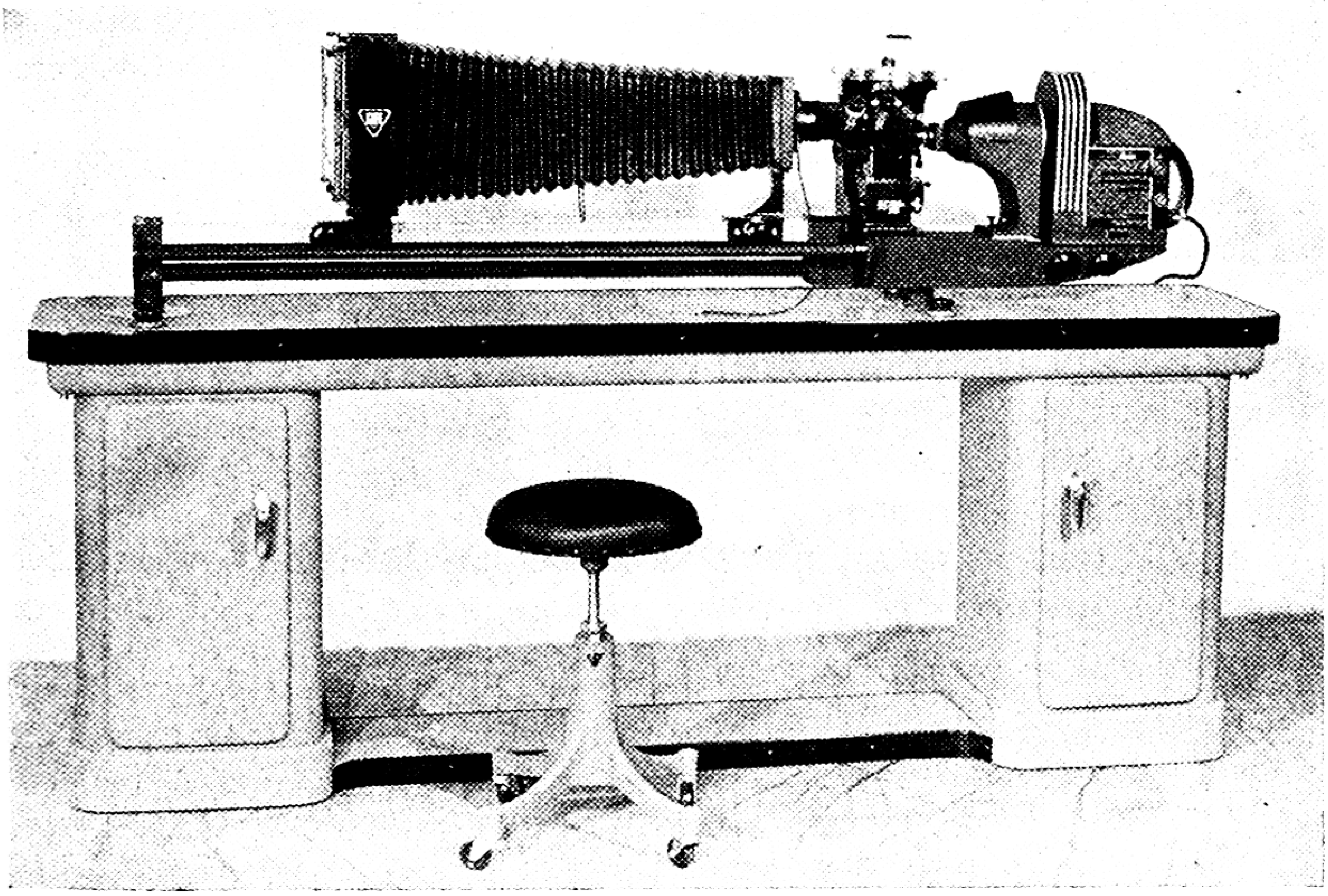


Fig. 15-13. Metalloscope for research work. *Courtesy Bausch & Lomb Optical Co.*

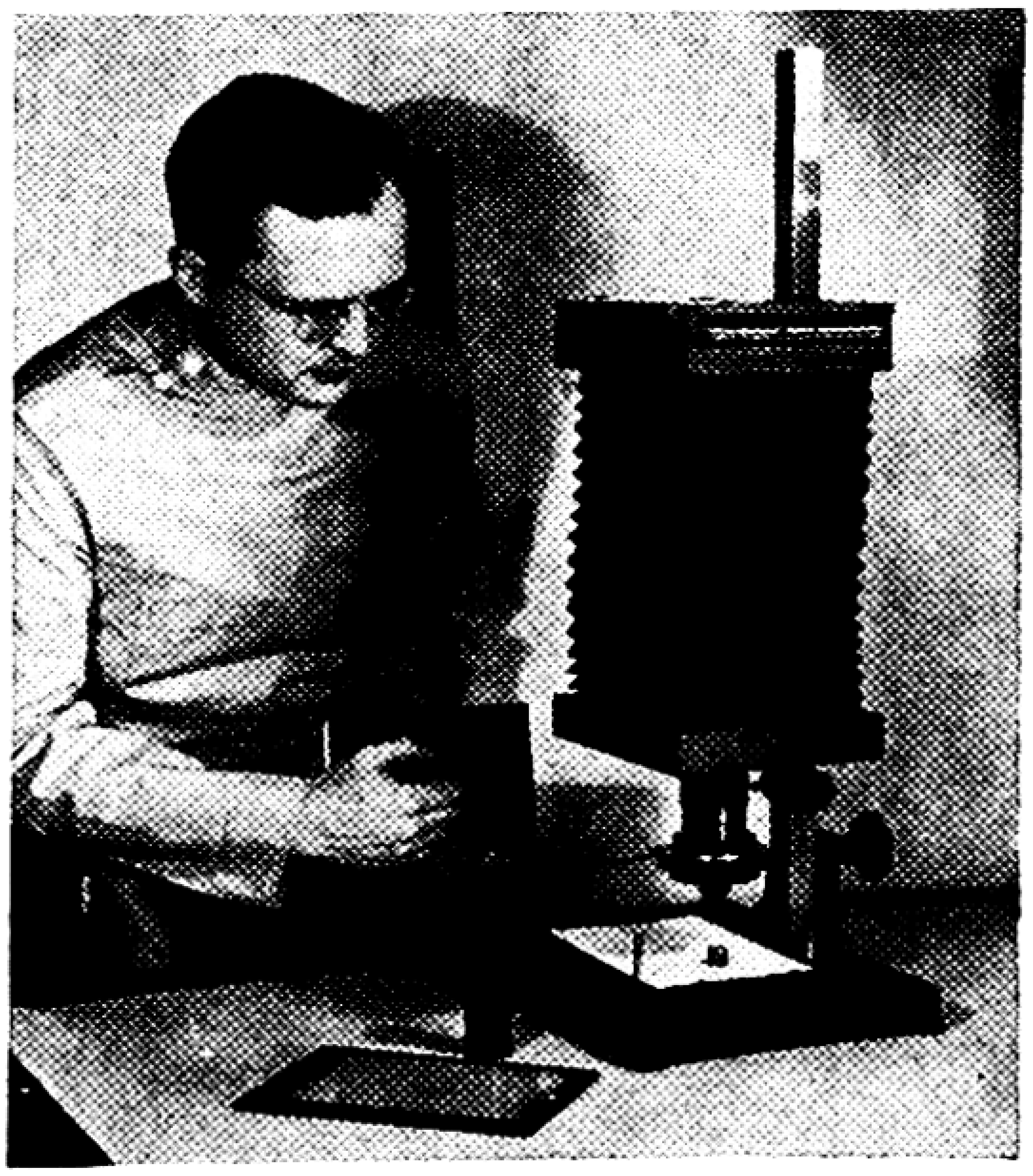


Fig. 15-14. Camera for low-power photomicrography. *Courtesy Bausch & Lomb Optical Co.*

Figure 15-13 shows a large metalloscope which is mounted on a vibration-absorbing mount. Both high and low magnifications are possible with this equipment.

Macro-inspection. Often defects, flow lines, inclusions, and depth of casings which would otherwise be invisible will appear if the metal is etched with a deep etch using a 10% solution of nitric acid in alcohol. If a very deep etch is desired, a 50% solution of hydrochloric acid in water at about 170 F can be used. This process is used to bring out flow lines in forgings.

Some specimens can be etched directly after grinding or machining, but others need to be fine-ground to bring out the detail.

Special cameras with magnifications of from 1X to 40X are made for macrophotography or for low-power microphotography. Such a camera is shown in Fig. 15-14.

DEFINITIONS AND SUMMARY

The steps in microphotography are:

(1) Obtain sample.
(2) Polish sample.
(3) Etch sample.
(4) Inspect sample with proper magnification.
(5) Photograph sample if a permanent record is desired.

In preparing the specimen:

(1) Do as little work on the specimen as possible.
(2) Round the edges of the mount to help the even flow of abrasives.
(3) Use as small a specimen as possible to save time.
(4) Wash thoroughly after each step.

Microscopic examination requires correct lighting and correct magnification for the best results.

PROBLEMS

1. List the steps in microphotography.
2. Distinguish between micro and macro photography.
3. Discuss the methods of obtaining samples.
4. Why is cleanliness so important in preparing a sample?
5. Why are metals etched before microscope inspection?
6. Why is macro-inspection used?
7. Discuss the types of microscope illumination.
8. What is resolution?
9. What is depth of focus?
10. List and discuss several polishing methods.

APPENDIX

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Chemistry deals with the properties of homogeneous bodies and with the changes which alter the identity of these substances.

Matter, from a chemical viewpoint, is made up of two types of substances: elements and compounds. An *element* can be defined as a substance which cannot be separated by ordinary chemical means into substances having properties different from itself.

A *compound* is a substance formed by the chemical combination of elements. It has definite proportions of the elements by weight. The proportions and properties of a compound are always the same regardless of the method of making the compound.

Chemical changes can be thought of as the redistribution of atoms or groups of atoms. An *atom* can be defined as the smallest particle into which an element may be divided and yet retain its properties. An atom may be divided, but the properties change. A *molecule* is the smallest particle into which a compound may be divided and yet retain the properties of the compound. A molecule is made up of a definite number of atoms. Consequently, elements in a given compound have definite proportions.

Each element has a symbol (Fe for iron). The symbol indicates several things:

1. The element itself.
2. One atom of that element.
3. The atomic weight of the element.

The *atomic weight* of an atom is the relative weight of an atom of a substance compared to the weight of an atom of oxygen. The atomic weight of an atom of oxygen is assumed to be 16. *Molecular weight* is the sum of the atomic weights of all the atoms of a molecule.

A subscript on a symbol, such as O_2, indicates the number of atoms of that substance in a given molecule.

The relative number of atoms in a material can be shown by a formula, which is always the same for a given substance. For instance, hemetite has the formula Fe_2O_3, which means that a molecule of hemetite contains two atoms of iron and three atoms of oxygen. Since the atomic weight of iron is about 56 and that of oxygen is 16, there must be $2 \times 56 = 112$ parts by weight of iron, and $3 \times 16 = 48$ parts of oxygen in the compound. The percentage of iron by weight would be $\frac{112}{112 + 48} \times 100 = 70\%$, and the percentage of oxygen would be $\frac{48}{112 + 48} \times 100 = 30\%$.

Chemical equations show the chemical changes that take place in a reaction. The equations are made up of formulas. Because of the *law of conservation of mass*, which states that the total mass of the substances entering into a chemical reaction equals the total mass of the products (neglecting any difference due to change in energy), a definite equation of atoms can be made up. These equations, which describe chemical reactions, must have the same number of each atom on each side of the equation, and, as a result, the same weight of material. In order to show the same number of atoms on each side of an equation, a process known as *balancing the equation* is performed. As an example, in a blast furnace, carbon takes the oxygen from P_2O_5 to make CO and leave phosphorous:

$$P_2O_5 + C \rightarrow P + CO$$

A count of the atoms of each element on each side of the arrow shows they are not equal. There must be five atoms of O on the right side as well as on the left. Then,

$$P_2O_5 + C \rightarrow P + 5CO$$

Also, there must be two atoms of phosphorous on the right side,

$$P_2O_5 + C \rightarrow 2P + 5CO$$

Checking over the equation shows that only carbon is unbalanced.

$$P_2O_5 + 5C = 2P + 5CO$$

This last equation is a true equation and is balanced.

Equations can be used to predict results and to figure amounts of material involved in a chemical reaction. The prediction of products is somewhat beyond the scope and need of this outline, but the figuring of quantities of material is of definite interest.

Two chemical reactions are of major interest to the metallurgist: one is reduction, and the other is oxidation. *Reduction* is the decreasing of the oxygen content of a compound, and *oxidation* is the increasing of the oxygen content of a compound.

Example:

Given the compound hemetite Fe_2O_3. How much carbon would be required to completely reduce the material to get 100 pounds of Fe? The equation is:

$$\begin{array}{cccccccl} 2Fe_2O_3 & + & 3C & = & 4Fe & + & 3CO_2 & \\ 2(112+48) & & 3\times 12 & & 4\times 56 & & 3(12+32) & \rbrace\ \text{molecular} \\ 320 & & 36 & & 224 & & 132 & \ \ \text{weights} \end{array}$$

This equation shows that the masses of each side of the equation are equal, for there are 356 units on each side.

Proportions can now be set up with the actual weight of the 224 units of Fe equivalent to 100 pounds. Thus,

$$\frac{C\ \text{lb}}{36} = \frac{100\ \text{lb}}{224}$$

$$C\ \text{lb} = \frac{100 \times 36}{224}\ \text{lb} = 16.1\ \text{lb carbon}$$

TABLE OF SOME ELEMENTS SHOWING ATOMIC WEIGHTS AND PROPERTIES

Element	*Symbol*	*Atomic Weight*	*Density lb/in.*^{3}	*Melting Point °F*
Aluminum	Al	26.97	0.0975	1214.6
Antimony	Sb	121.76	0.2391	1166.9
Beryllium	Be	9.02	0.0658	2345
Bismuth	Bi	209.00	0.3541	519.8
Cadmium	Cd	112.41	0.3125	609.6
Calcium	Ca	40.08	0.0560	1564
Carbon	C	12.01	0.0802	
Chromium	Cr	52.01	0.2579	2822
Cobalt	Co	58.94	0.3216	2714
Copper	Cu	63.57	0.323	1981.4
Gold	Au	197.2	0.6973	1945.4
Hydrogen	H	1.008	0.3026×10^{-5}	−434.4
Iron	Fe	55.84	0.284	2795
Lead	Pb	207.21	0.409	621.2
Lithium	Li	6.940	0.0193	366.8
Magnesium	Mg	24.32	0.0628	1204
Manganese	Mn	54.93	0.268	2268
Mercury	Hg	200.61	0.489	−38.0
Molybdenum	Mo	95.95	0.368	4748
Nickel	Ni	58.69	0.322	2646
Nitrogen	N	14.008	4.209×10^{-5}	−345.87
Oxygen	O	16.000	4.812×10^{-5}	−361.12
Phosphorous	P	31.02	0.0657	111.4
Platinum	Pt	195.23	0.774	3224
Silicon	Si	28.06	0.087	2600
Silver	Ag	107.88	0.38	1761
Sulphur	S	32.06	0.075	235.4
Tantalum	Ta	180.88	0.60	5162
Tin	Sn	118.70	0.264	449.6
Tungsten	W	183.92	0.698	6098
Vanadium	V	50.95	0.205	3110
Zinc	Zn	65.38	0.258	787

In the making of steel, many reactions involve acids and bases. Most of the metals in molten steel are present as oxides. Since these oxides are liquid at that high temperature, they react as if in a water solution. Oxides of nonmetals are *acids;* oxides of metals are *bases.* Since acids and bases react very easily when brought together, care must be observed in the choice of furnace linings.

Copper-Nickel · Alloys (5 to 40% Ni)

A Compilation of Common Specifications

Name	Characteristics	Specification	Form or Grade	Composition, Per Cent Cu	Ni	Sn	Pb	Zn	Others (max.)
Cupro-nickel (80-20)	Has high corrosion and heat resistance.	—	Condenser tubes.	80	20	—	—	—	—
Cupro-nickel (70-30)	The greatest resistance to corrosion of all cupro-nickels. Used in marine and oil refinery installations.	ASTM B171,[1] Copper-nickel	Copper - alloy condenser tube plates.	Rem.	29.00-33.00	1.50 max.	0.05 max.	1.00 max.	Mn 1.00 Fe 0.50
		ASTM B111,[2] 70-30 Copper-nickel	Seamless condenser tubes and ferrule stock.	Rem.	29.00-33.00	1.50 max.	0.05 max.	1.00 max.	Mn 1.00 Fe 0.50
		ASTM B122,[3] Alloy No. 5	Sheet and strip.	Rem.	29.00-33.00	1.50 max.	0.05 max.	1.00 max.	Mn 1.00 Fe 0.50
Leadel nickel bronze (leaded nickel silver)	These cast alloys have good machinability and a silvery color. They make good sound corrosion resistant castings.	ASTM B30, Alloy No. 11B	For sand castings.	64.00-66.00	24.00-26.00	4.50-5.50	1.00-2.00	1.00-3.00	Mn 1.00 Fe 0.50
		ASTM B149, Alloy No. 11B	Sand castings.	64.00-67.00	24.00-27.00	4.00-5.50	1.00-2.50	1.00-3.00	Mn 1.00 Fe 1.00
		ASTM B30, Alloy No. 11A	For sand castings.	63.00-65.00	19.50-21.00	3.50-4.50	3.00-5.00	7.00-10.00	Mn 1.00 Fe 1.00
		Fed. WWP 541	Sand castings.	62.0 min.	19.0 min.	2.5 min.	6.0 max.	10.0 max.	Mn 1.00
Nickel brass (nickel silver)	These wrought alloys have good mechanical properties, corrosion resistance and can be hot or cold worked; often used as springs and contacts in electrical apparatus, and sometimes for small caliber bullet jackets.	ASTM B111,[2] 80-20 Copper-nickel Type A	Seamless condenser tubes and ferrule stock.	Rem.	19.0-23.0	1.0 max.	0.05 max.	1.00 max.	Mn 1.0 Fe 0.5
		ASTM B111,[2] 80-20 Copper-nickel Type B	"	Rem.	19.0-23.0	1.0 max.	0.05 max.	3.0-6.0	Mn 1.0 Fe 0.5
		ASTM B122,[3] Alloy No. 6	Sheet and strip.	Rem.	19.0-23.0	1.00 max.	0.05 max.	3.00-6.00	Mn 1.00 Fe 0.50
		ASTM B122,[3] Alloy No. 7	Sheet and strip.	Rem.	19.0-23.0	1.00 max.	0.05 max.	3.00-6.00	Mn 1.00 Fe 0.50

Leaded nickel bronze (leaded nickel silver)	The lead improves the machinability but prohibits heat treatment; has good resistance to corrosion.	ASTM B149 Alloy No. 11A	Leaded nickel-bronze sand castings.	63.00-67.00	19.50-21.50	3.50-4.50	3.00-5.00	6.00-10.00	Mn 1.00 Fe 1.00
Nickel brass (nickel silver)	A pleasing white color; can be stamped, spun, cold-formed and drawn, or hot forged; they have good corrosion resistant qualities; used in condenser tubes and chemical piping.	SAE 42	White nickel brass castings.	55.00-64.00	18.00 min.	—	—	Rem	Fe 0.35
		ASTM B122[3], Alloy No. 1	Copper-nickel alloy sheet and strip.	70.5-73.5	17.0-19.5	—	0.10 max.	Rem.	Mn 0.50 Fe 0.35
		ASTM B122,[3] Alloy No. 2	"	63.0-66.5	17.0-19.5	—	0.10 max.	Rem.	Mn 0.50 Fe 0.35
		ASTM B122,[3] Alloy No. 4	"	53.5-56.5	17.0-19.5	—	0.10 max.	Rem.	Mn 0.50 Fe 0.35
	General purpose material in several tempers.	ASTM B151,[4] Alloy A	Copper-nickel-zinc alloy rod and wire.	63.0-66.5	17.0-19.5	—	0.05 max.	Rem.	Mn 0.50 Fe 0.25
	Generally used in the hard temper.	ASTM B151,[4] Alloy B	"	53.5-56.5	17.0-19.5	—	0.05 max.	Rem.	Mn 0.50 Fe 0.25
	Machinability better than alloys A or B.	ASTM B151,[4] Alloy C	"	60.0-65.0	17.0-19.5	—	0.75-1.25	Rem.	Mn 0.50 Fe 0.25
Leaded nickel brass (leaded nickel silver)	Used where corrosion resistance and / or pressure tightness is needed. Plumbing and architectural fixtures and fittings.	ASTM B30, Alloy No. 10B	Copper-base ingot for sand castings.	58.00-61.00	15.50-17.00	2.50-3.50	4.50-5.50	Rem.	Mn 0.50 Fe 1.00
		ASTM B149, Alloy No. 10B	Leaded nickel brass sand castings.	57.00-62.00	15.00-17.50	2.25-3.75	4.25-5.75	Rem.	Mn 0.50 Fe 1.50
		ASTM B149, Alloy No. 10A	"	53.00-58.00	11.00-14.00	1.50-3.00	8.00-11.00	Rem.	Mn 0.50 Fe 1.50
		ASTM B30, Alloy No. 10A	Copper-base ingot for sand castings.	53.00-58.00	11.00-14.00	1.50-3.00	8.00-11.00	Rem.	Mn 0.50 Fe 1.00
	A general purpose alloy.	—	Sand castings.	Rem.	5.0-5.5	5.0-5.5	nil	1.0-2.0	P 0.03-0.05

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Low Melting Alloys

	Part	Fusible Alloy	M.P. (F.)	Composition, %	Use
Alloys for Safety Devices	Boiler Plugs	Tin		Sn, sometimes small amounts of Pb	Bronze plugs filled with tin and screwed into boiler at lowest safe water level, to melt when level is reached.
	Sprinkler System Plugs	Woods metal or modification, 160 F pattern	about 163 F.	50 Bi, 25 Pb, 12.5 Cd, 12.5 Sn	To release water spray when air temperature reaches prescribed point.
		200 F pattern		52 Bi, 32 Pb, 16 Sn	Used in tropical climates or industrial applications where continued heat may cause the 160 F. alloy to creep below its fusing point.
		212 F. pattern		50 Bi, 31 Pb, 19 Sn	
		286 F. pattern		50 Bi, 50 Pb; or 56 Bi, 44 Pb	
		360 F. pattern		33-1/3 Pb, 66-2/3 Sn; or 37 Pb, 63 Sn	
	Chlorine Cylinder Plugs	Lipowitz metal	160 F.	50 Bi, 26-2/3 Pb, 13-1/3 Sn, 10 Cd	To prevent overheating of compressed gas.
	Some alloys, or slight modifications, used for releasing automatic fire doors, operation of automatic fire alarms, protection of electric water-heaters or oil burners, etc.				
Alloys for Solders	Standard 50-50 Solder			50 Pb, 50 Sn	Formerly the general purpose soft solder; now replaced for most work by low-tin emergency formulas. Tensile strength about 6400 p.s.i.
	S.T. Solders		above 580 F.	Pb + 1¼, 2½, 5 Ag	Wartime solders designed to save tin; tensile strength about 5000 p.s.i.
	Pewter Solder			50 Bi, 25 Sn, 25 Pb	For soldering pewter and similar low-melting alloys for which standard solders would not be suitable.
	Glass Solders	Woods metal	165 F.		May be used for glass-to-glass or metal-to-glass joints. Compositions with indium are especially useful in this field.
	Fusible alloys are also used for soldering parts subject to damage at higher temperatures, as wax-filled radio condensers, etc. Addition of a few per cent of indium increases wetting properties and lowers m.p.				

Alloys for Molds or Patterns	Patterns	Cerrobase	255 F.	58 Bi, 42 Pb	For permanent metal patterns, match plates, proof castings, etc. Cerrobase has no shrinkage upon cooling so that metal patterns can be made from a wood master pattern without allowing for double shrinkage.
		Cerrosafe	160 F.		
	Molds	Cerrobase	255 F.	58 Bi, 42 Pb	Metal, as Cu, electrodeposited on Cerrobase mold, which is then removed by melting out. Iron master model electrodeposited on Cerrobase negative, and molds for rubber, plastic, die casting, etc. formed from this.
		Cerrosafe	160 F.		
	Other low-melting alloys can be similarly used if complete absence of shrinkage is not required.				
Alloys for Tool Fabrication	Wood Pressing Dies	Cerromatrix	248 F.	48 Bi, 28.5 Pb, 14.5 Sn, 9 Sb	May be cast against a wood, etc., master carving, and other wood pieces pressed directly from this. Tensile strength about 13,000 p.s.i.
	Punches and Dies (Metal-working)	Cerromatrix	248 F.	48 Bi, 28.5 Pb, 14.5 Sn, 9 Sb	Punches, etc., located in punch plate and anchored by molten alloy. Dies for metal-forming where runs are short may be cast in this alloy. Repair of tools and dies.
	Magnetic Chucks	Cerromatrix	248 F.	48 Bi, 28.5 Pb, 14.5 Sn, 9 Sb	Highly diamagnetic, hence used to separate pole pieces on magnetic chucks.
Alloys for Metal Forming	Filler or Embedding Material	Woods metal (Cerrobend)	160 F.	50 Bi, 26.7 Pb, 10 Cd, 13.3 Sn,	Metal tubes filled with Woods metal, bent, and fusible alloy melted out by hot water. Hollow silverware embossed by filling silver tube with alloy, swaging on the design, and melting out fusible metal. Irregular forms, as metal molding, embedded in fusible alloy for bending. Irregular objects embedded in fusible alloy to permit chucking in lathe, etc., for machining.
	Master for Profiling	Woods metal, etc.	160 F.	50 Bi, 26.7 Pb, 10 Cd, 13.3 Sn	A negative casting made from a wooden or plaster mold may be used for a guide in profiling machines.
Miscellaneous Alloys		Anatomical alloy	140 F.	53.5 Bi, 19 Sn, 17 Pb, 10.5 Hg	For embedding animal tissues.
		Rose's alloy	212 F.	50 Bi, 28 Pb, 22 Sn; or 46 Bi, 20 Pb, 34 Sn	Has comparatively high tensile strength--about 8000 p.s.i.
		Dental amalgam		Hg plus a finely divided alloy of Ag, Sn, Cu	Sets up hard after mixing. For filling dental cavities.
		Modified Lipowitz alloy	116 F.	18.3 indium added	Greater resistance to oxidation at high temperatures, and greatly lowered m.p.
			--76 F.	91.5 Hg. 8.5 Tl	Suggested for use in thermometers to read to —74 F.
Miscellaneous Uses	For metallizing of wood, as patterns; for tempering baths to be used at low temperatures; as a liquid seal for gas atmosphere furnaces, etc.				

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TEMPERATURE SCALE CONVERSION FORMULA

To change from Fahrenheit to Centigrade:

$$C = \tfrac{5}{9}(F - 32)$$

To change from Centigrade to Fahrenheit:

$$F = \tfrac{9}{5}C + 32$$

SUGGESTED EQUIPMENT FOR A METALLURGICAL LABORATORY

The following list of equipment will provide laboratory work on:

1. Heat-treating of all types
2. Powder metallurgy
3. Austempering
4. Macrographic work
5. Micrographic work
6. Surface inspection
7. Spectrographic analysis
8. Grain size determination

This equipment, in conjunction with a materials testing laboratory, would give a well-rounded laboratory program in metallurgy. The list is meant to be a guide only, for there are many makes of equipment on the market having a wide range of prices. The cost of the following list would be between $4500.00 and $5500.00.

20- to 30-ton hydraulic press for making powder metallurgy specimens.
Punch and die for making powder specimens.
Specimen cutter with coolant circulating pump.
Double-end grinder.
Plastic mounting press.
Two standard and one slow-speed polishing machines mounted in a table.
Electric furnace with pyrometer and rheostat or automatic control.
Gas furnace capable of heating to 2300 F.
Small pot furnace.
Immersion-type pyrometer.
Two metallurgical microscopes.
Camera attachment for microscope.
Low-power camera.
Focusing glass.
Surface inspector.
Grain-size eyepiece.
Darkroom equipment:
  Sink
  Projection printer
  Contact printer
  Washer
  Drier

- Pans
- Paper cutter
- Safe lamp

Spectrograph with equipment for d-c and a-c source.
Rockwell hardness tester.
Chemical sink.
Laboratory lamp.
Storage cabinets and benches.

OUTLINE OF A LABORATORY COURSE IN ELEMENTARY METALLURGY

The following are brief descriptions of laboratory experiments that might accompany an elementary metallurgy course:

(Additional information concerning heat-treatments, etchants, polishing methods, and photographic techniques can be found in the American Society of Metals publication *Metals Handbook*.)

1. Determine the upper critical temperatures of several pieces of steel by testing with a magnet. Increase the temperature of the furnace in 25 F increments, and allow the test piece to come up to the furnace temperature before testing for loss of magnetism. The steel loses its magnetism at the upper critical temperature. Quickly quench the test piece in water at the first temperature at which the metal is para-magnetic, and check the hardness.
2. Harden several pieces of high-carbon steel. Temper at temperatures varying from 400 F to 1000 F. Examine grain structures and grain sizes.
3. Heat one specimen of high-carbon steel to just above the upper critical temperature and quench immediately. Heat a second specimen 200 F above the upper critical temperature, hold it there for one-half hour, and then quench. Compare grain structure and grain size.
4. Cyanide a piece of low-carbon steel. Polish, etch, and examine a cross section of the cyanided steel.
5. Carburize a piece of low-carbon steel. Break the specimen and study one cross section as broken. Polish, etch, and inspect the other.
6. Heat a piece of high-carbon steel above the upper critical temperature and quench in a bath at 1000 F. Allow the piece to remain in the bath until transformation is complete. Examine grain structure. Repeat, using other quenching temperatures.
7. Polish, etch, and examine specimens of gray cast iron, white cast iron, and malleable iron. Compare grain structures.
8. Macroetch a steel forging and examine for flow lines.
9. Weld two pieces of hardened high-carbon steel together. Find Rockwell hardness at varying distances from the weld. Study grain structure at varying distances from the weld.
10. Heat three pieces of 60/40 brass to 1525 F for one-half hour. Quench one in water, cool one in air, and cool one slowly in the furnace. Etch and compare the grain structures.
11. Cold-forge a piece of 70/30 brass to about one-half cross-section area. Cut into two pieces. Etch and examine one as is; heat the other to 1475 F for one-half hour, then etch and examine.

12. Anneal a piece of duralumin (17S) by heating to about 660 F and cool at a rate of not over 50 F per hour until 500 F is reached. It may then be cooled in air to room temperature. Check the hardness.

Heat the metal to 950 F and quickly quench in water. Check the hardness immediately and then check every 24 hours for four days while it ages.

13. Microphotograph several etched specimens. Develop and print the pictures.

14. Macrophotograph several specimens. Develop and print the pictures.

15. Make spectrographs of several metals and analyze the metals qualitatively. If a densitometer is available, analyze quantitatively.

SUGGESTED EQUIPMENT FOR A MATERIALS TESTING LABORATORY

Universal testing machine with accessories
Impact testing machine
Torsion testing machine
Fatigue testing machine
Rockwell hardness tester
Brinell hardness tester
Extensiometer
Micrometer
Thread micrometer
Dividers
Specimen marking tool
Bench lathe for making specimens
Milling machine for making specimens

The above equipment would provide laboratory work in most of the standard tests. The cost would be somewhere between $8000.00 and $10,000.00.

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